Impact of freezing of subgrade on pavement deformation

L'impact de la gelée de la couche de forme sur la déformation du revêtement de route

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ABSTRACT: Displacement, strains and stresses values in characteristic points of pavement and subgrade of a highway during various year seasons were obtained in the paper with the use of multilayer elastic half-space model. Elastic characteristics of asphalt concrete layers and soil have been given depending on temperature. Temperature and moisture values have been obtained through the use of special sensors. Calculations showed that displacement, strains and stresses in points of pavement structure and subgrade are considerably varied depending on seasonal temperature values of asphalt concrete layers and temperature and moisture of soil.

RÉSUMÉ: Dans le présent article, en utilisant le modèle du demi-espace multicouche élastique, les valeurs du déplacement, la déformation et la mise en tension dans des points figuratifs du revêtement de route et de la couche de forme de la route ont été identifiés dans les différentes saisons de l'année. Les propriétés élastiques de chape du bitume et de sol ont été choisis en fonction de la température. Les valeurs de température et d'humidité ont été obtenus à l'aide des capteurs spéciaux. Les calculs ont montré que le déplacement, la déformation et la mise en tension dans les points de configuration du revêtement de route et de la couche de forme changent considérablement en fonction des valeurs saisonniers de la température des chapes du bitume, la température et l'humidité du sol.

KEYWORDS: highway, subgrade, pavement, freezing, strain, stress.

1 INTRODUCTION

As it is known, the main elements of the highway, which provide its strength and durability, are pavement structure and subgrade (Yoder and Witczak 1975, Papagiannakis and Masad 2008, Huang 2004), and they are considered simultaneously during design (ARA 2004, ST RK 2007, ODN 2001, TKR 2007).

The strength of subgrade impacts greatly on the strength of the highway. If the subgrade is constructed from clay soil, then its strength and deformation characteristics depend greatly on moisture. Numerous research results, including the works (Liu 2013, Shin et al. 2013, Teltayev 2012, Teltayev 2013, Teltayev et al. 2015, Teltayev and Aitbayev 2015a, Teltayev and Aitbayev 2015b) showed that temperature and moisture in points of subgrade vary considerably during annual period, and part of moisture, contained in points of subgrade, is transferred to frozen condition (ice) during winter period. Mechanical and other characteristics of frozen soil depend on negative temperature, as well as on initial moisture and amount of unfrozen water.

This paper represents the results of experimental research for temperature and moisture variation in subgrade of the highway and evaluation of impact of freezing of subgrade on pavement deformation.

2 EXPERIMENTAL RESEARCH OF TEMPERATURE AND MOISTURE IN THE HIGHWAY

2.1 *Experimental section*

The section with asphalt concrete (km 76+30) pavement of "Astana-Burabai" highway was 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. Highway has 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 (Figure 1) consists of the following layers: 1- stone mastic asphalt concrete, 6 cm; 2 – dense asphalt concrete, 9 cm; 3 – crushed stone treated with bitumen, 12 cm; 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 %. Underground water is deep (lower than 3.0 m).

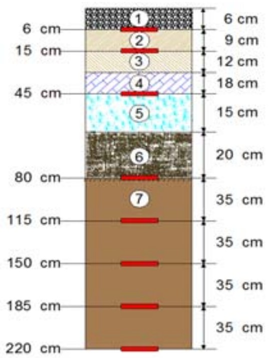

Figure 1. Scheme for location of sensors in pavement structure and subgrade for section with asphalt concrete pavement of "Astana-Burabai" highway: 1…6 – numbers of pavement layers; 7 – subgrade; - temperature and moisture sensors

2.2 *Temperature and moisture sensors*

Company "Interpribor" (Chelyabinsk, Russia) produced temperature and moisture sensors on 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.

Figure 2 shows general view of one set of sensors visually.

Figure 2. One set of temperature and moisture sensors

Temperature element of sensors was calibrated by the producer and moisture element was calibrated in the laboratory of KazdorNII. Calibration of sensors was performed with the use of soils, selected from the areas of their installation. Measurement ends of the sensors were put on the surface of the highway and fixed in measurement chamber of land system of the set (Figure 3).

Figure 3. Measurement (land) system for set of temperature and moisture sensors

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 depths for their installation, calculated from pavement surface, were equal to: 6, 15, 45, 80, 115, 150, 185 and 220 cm.

2.3 *Temperature and moisture in subgrade and pavement*

Figure 4 shows the graphs of temperature distribution in the depth of highway during various seasons of the year, constructed under experimental data, which were obtained through the use of sensors. As it is seen, temperature distributions differ greatly from each other during various seasons of the year. As expected, the biggest temperature values occur in summer and with temperature decrease in autumn temperature reduction occurs also in subgrade. Subgrade (1.50 cm) and ground foundation in winter are in frozen condition. Temperature of subgrade surface reduces to -12ºC. Pavement and subgrade start defrosting in the beginning of spring from top to bottom.

Figures 5-7 show the graphs for moisture distribution in the depth of subgrade during various seasons of the year, where it can be seen that moisture values in points of subgrade are almost the same in summer and autumn seasons of the year. Part of water, contained in points of subgrade, is transferred to ice in winter with negative temperatures occurrence. Continuous line in Figures 6 and 7 shows moisture content in liquid condition (unfrozen water), and dashed line corresponds to initial moisture (before winter). It can be seen that frozen water content (ice) in subgrade decreases during winter period with the depth increase (Figure 6). Defrosting of subgrade in spring occurs from top to bottom. It is clearly seen from Figure 7, that upper part of subgrade defrosted to 130 cm in the end of April 2014, and the rest part of subgrade is in frozen condition.

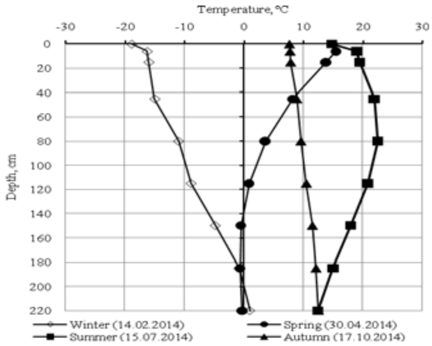

Figure 4. Temperature distribution in the depth of highway during various seasons of the year

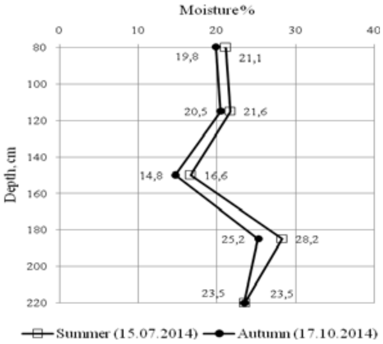

Figure 5. Moisture distribution in the depth of subgrade in summer and autumn periods of the year

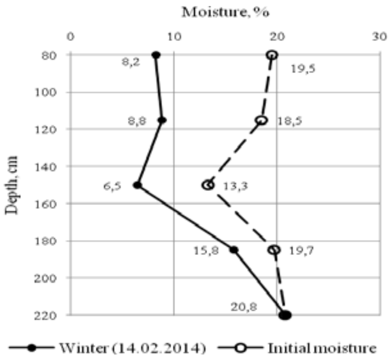

Figure 6. Moisture distribution in the depth of subgrade in winter period of the year

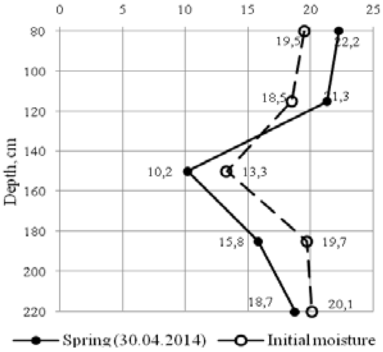

Figure 7. Moisture distribution in the depth of subgrade in spring period of the year

It is clear from the graphs of temperature and moisture variation (Figures 8 and 9) on subgrade surface (80 cm) and in the depth of 115 cm, that sharp decrease of moisture occurs in winter approximately at the moment of temperature transition to negative area, and moisture is also decreases with further temperature reduction. And in spring there is intermittent increase of moisture during temperature transition from negative area to positive area. Certainly, these phenomena show phase transitions, which occur at temperature, approximately equal to 0ºC.

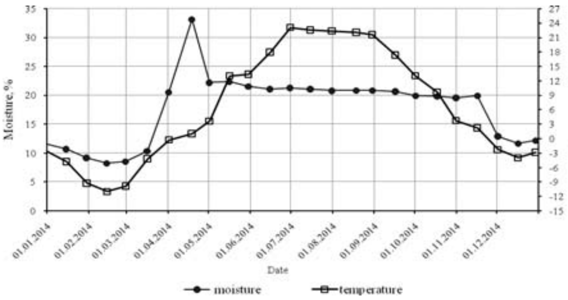

Figure 8. Temperature and moisture variation on subgrade surface (80 cm)

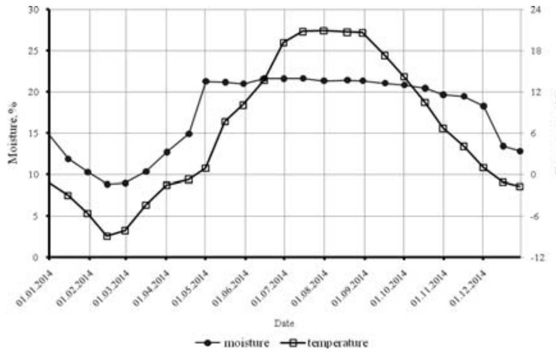

Figure 9. Temperature and moisture variation in subgrade (115 cm)

3. STRESSES AND STRAINS IN THE HIGHWAY

3.1. *Mechanical characteristics of materials and soil*

Elasticity moduli values of stone mastic and porous asphalt concretes at temperatures, corresponding to various seasons of the year, were calculated under modified formula of Hirsh (Christensen and Bonaquist 2015). For this formula the elasticity modulus of bitumen was calculated under the formula, which was given in the work (Teltayev and Radovskiy 2016). Poisson's coefficient values at different temperatures were calculated under the formula, which was recommended by Guide (ARA 2004). Elasticity moduli and Poisson's coefficient values for asphalt concretes are represented in Table 1.

Table 1. Temperature and elasticity moduli for asphalt concretes

Season of the year		Winter	Spring	Summer	Autumn
Tempera-ture T, ºC	Stone mastic asphalt concrete	-17.6	15.2	16.9	7.8
	Porous asphalt concrete	-16.2	14.7	19.3	7.9
Elasticity modulus E, MПa	Stone mastic asphalt concrete	11 230	3 080	2 830	4 330
	Porous asphalt concrete	8 570	2 270	1 800	3 150
Poisson's coeffi-cient	Stone mastic asphalt concrete	0.15	0.32	0.33	0.26
	Porous asphalt concrete	0.16	0.36	0.38	0.31

Elasticity modulus values for soil of subgrade (sandy clay loam) at positive temperatures are fixed under standard document (ST RK 2007), and at negative temperatures they are determined under data of Prof. N.A. Tsytovich (Tsytovich 1973) (Tables 2 and 3). Due to absence of reliable data Poisson's coefficient value was adopted as constant and equal to 0.35.

Table 2. Temperature and elasticity modulus values for soil of subgrade

Season of the year	Factors	Depth, cm				
		80	115	150	185	220
Winter	Temperature T, ºC	-11,0	-8,9	-4,8	-0,8	1,0
	Elasticity modulus E, MПa	9 840	9 790	6 660	1 250	72
Spring	Temperature T, ºC	3,6	0,9	-0,5	-0,6	-0,3
	Elasticity modulus E, MПa	55	68	800	960	500
Summer	Temperature T, ºC	22,5	20,8	18,0	15,0	12,5
	Elasticity modulus E, MПa	68	63	108	28	46
Autumn	Temperature T, ºC	9,6	10,5	11,5	12,1	12,5
	Elasticity modulus E, MПa	83	76	108	38	46

Table 3. Mean values of elasticity modulus for soil of subgrade

Season of the year	Winter	Spring	Summer	Autumn
Mean values of elasticity modulus E, MПa	5522	477	63	70

Elasticity modulus and Poisson's coefficient values of the materials for the rest of pavement layers were determined under standard document (ST RK 2007) and represented in Table 4.

Table 4. Elasticity modulus and Poisson's coefficient values of the materials for the pavement layers

Material	Elasticity modulus E, MPa	Poisson's coefficient ν
Crushed stone treated with bitumen	600	0.25
Crushed stone sand mix treated with cement (7 %)	500	0.25
Crushed stone sand mix	230	0.30
Sand	120	0.30

3.2. *Calculation of stresses and strains*

Calculation scheme of pavement structure and subgrade of highway is represented in Figure 10. The figure shows maximum deflection of the surface layer u_{z0}, horizontal stress σ_{r2} and horizontal strain ε_{r2} on the bottom surface of the second asphalt concrete layer, maximum vertical strain on the subgrade surface ε_{zsq}. These indicators characterize better the performance of the highway under multiple impact of truck loading, and they are considered during design of pavement structures (ARA 2004, ST RK 2007, ODN 2001, TKR 2007). Multilayer elastic half-space model was used for their calculation (Privarnikov 1973). Uniform load q = 0.6 MPa affects the asphalt concrete pavement surface within the circle with diameter of D = 42 cm. Such load corresponds to axle load Q = 13 tons.

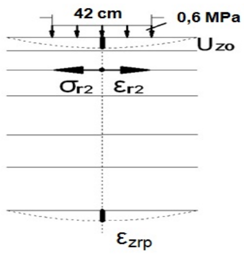

Figure 10. Calculation scheme of pavement structure and subgrade of highway

A software has been developed for the computer, which realizes Privarnikov's model, and values for characteristic factors u_{z0}, σ_{r2}, ε_{r2}, ε_{zsq} have been calculated through its use (Table 5). One can see from the table that maximum deflection occurs in summer and in autumn. Its values are two times more during these seasons than in spring, and they are three times more than in winter. The biggest value of tensile stress in the second asphalt concrete layer was obtained in winter, which was practically three times more than in spring and in summer and two times more than in autumn. Tensile strain in the second asphalt concrete layer has the biggest value in spring and in summer. Vertical compression strain on the subgrade surface has maximum value in summer, which is 55, 4 and 11 times more than in winter, in spring and in autumn respectively.

Therefore, it became clear that due to temperature variation in asphalt concrete layers and temperature and moisture variation in points of subgrade during annual cycle, displacements, strains and stresses in characteristic points of pavement structure and subgrade were considerably varied.

Table 5. Displacement, stress and strain values in points of pavement and subgrade.

Year season	Deflection u_{z0}, mm	Stress σ_{r2}, MPa	Strain ε_{r2}, $\mu\varepsilon$	Strain ε_{zsq}, $\mu\varepsilon$
Winter	0.202	1.071	110	6.6
Spring	0.343	0.381	160	82
Summer	0.697	0.261	160	360
Autumn	0.622	0.559	150	32

CONCLUSION

Temperature and moisture sensors give a chance to obtain valuable information for road practice and science regarding temperature and moisture variation in points of pavement structure and subgrade of the highway.

The results of experimental research with the use of sensors showed that temperature and moisture were distributed in points of pavement structure and subgrade during various seasons in different ways. Subgrade is in frozen condition in winter. Temperature of subgrade surface decreases to -12ºC.

Moisture distribution in subgrade is almost the same during summer and autumn seasons. Part of moisture is transferred to ice in points of subgrade in winter. Unfrozen water content decreases, and frozen water (ice) increases with the temperature reduction. Sharp fall of moisture occurs at negative temperature start in the beginning of winter, and sharp increase of moisture occurs at positive temperature start in spring, these are created by phase transitions.

Calculations showed that displacement, strains and stresses in points of pavement and subgrade structure are considerably varied depending on seasonal temperature values of asphalt concrete layers and temperature and moisture of soil.

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REFERENCES

ARA, Inc, ERES Concultans Division. 2004. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Final Report. NCHRP Project 1-37 A. Transportation Research Board of the National Academies, Washington.

Christensen D.W. and Bonaquist R.F. 2015. Impoved Hirch model for estimating the modulus of hot mix asphalt. Journal of the Association of Asphalt Paving Technologists 84, 527-562.

Huang Y.H. 2004. Pavement Analysis and Design. Second Edition. Pearson Education, Inc., Upper Saddle River, New Jersey.

Liu JK. 2013. Review of the influence of freeze-thaw cycles on the physical and mechanical properties of soil. Sciences in cold and arid regions 5 (4), 457–460.

ODN 218.046-01. 2001. Design of flexible pavements. Moscow.

Papagiannakis A.T. and Masad E.A. 2008. Pavement Design and Materials. John Wiley & Sons. Inc., New Jersey.

Privarnikov A.K. 1973. Volumetric deformations of multilayer basement. Stability and strength of structural elements. Dnepropetrovsk, 27–45.

Shin E., Ryu B., Kim K, et al. 2013. Evaluation of frost heaving susceptibility of subgrade soils using an indoor frost heaving system. Proceedings of the 5th International geotechnical symposium "Geotechnical engineering for disaster preventions and reduction, environmentally sustainable development". Incheon, Korea, 464–469.

ST RK 3.03-19-2006. 2007. Design of flexible pavements. Astana.

Teltayev B. 2012. Consideration of mechanical indices for soil basement while calculation of pavement structures. Proceedings of 4thCentral Asian Geotechnical Symposium "Geo-Engineering for Construction and Conservation of Cultural Heritage and Historical Sites. Challenges and Solutions". Samarkand, Uzbekistan, 218–223.

Teltayev B. 2013. Influence of mechanical indices for soil basement on strength of road structure. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering. Paris, 1365–1368

Teltayev B, Baibatyrov A. and Suppes E. 2015. Characteristics of highway subgrade frost penetration in regions of the Kazakhstan. The 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering. Fukuoka, Japan, 1664–1668.

Teltayev B. and Aitbayev K. 2015a. Modeling of temperature field in flexible pavement. Indian Geotechnical Journal 45 (4), 371–377.

Teltayev B. and Aitbayev K. 2015b. Modeling of transient temperature distribution in multilayer asphalt pavement. Geomechanics and Engeneering 8 (2), 133–152.

Teltayev B. and Radovskiy B. 2016. Low temperature cracking problem for asphalt pavements in Kazakhstan. 8th RILEM International Conference on Mechanics of Cracking and Debonding in Pavements, 1, 139–145.

TKP 45-3.03-2007. 2007. Highways. Flexible pavements. Instructions for design. Minsk.

Tsytovich N. A. 1973. Mechanics of frozen soils. Moscow.

Yoder E.J. and Witczak M.W. 1975. Principles of Pavement Design. John Wiley & Sons, Inc., New Jersey.