ESTIMATION OF THE CRACKING PROBABILITY IN ROAD STRUCTURES BY MODELING OF EXTERNAL INFLUENCES

Ivan Leonovich[1], **Irina Melnikova**[2] **(Irina Melnikova is a corresponding author)**

Dept. of Road Construction and Road Management, Belarusian National Technical University,
Pr. Niezavisimosti 65, 220013 Minsk, Belarus
E-mails: [1]bntu.nilsed@mail.ru; [2]rin_m@mail.ru

Abstract. This paper presents the initial study results of the process of crack appearance in asphalt pavements by reason of traffic load and temperature. Calculations were carried out using of finite element method (FEM). According to the modeling results one can predict an appearance of reflected cracks under the traffic load and cracks that occurred under the influence of temperature. Recommendations on the choice of the road structure are also presented in the paper.

Keywords: Asphalt concrete pavements, cracking, finite element method (FEM), modeling, stresses, deflection, climatic conditions, traffic load.

1. Introduction

The network of public roads in Belarus exceeds 418 km by 10 thousand square km of the territory. Roads with asphalt concrete pavements are the predominant. Reconstruction and works to improve transport characteristics of the main roads linking the major cities of the country with its capital – Minsk – are carrying out nowadays. Furthermore, as the Republic of Belarus is a transit country, road service is working on increasing road capacity from 10 to 11.5 and 13 tons per axle.

Durability of the road structure is one of the most important parameters of technical and operating condition of a road. It depends on an accepted base layer construction, the used materials and their aging, degradation of the road pavement, the external traffic load, capacity of traffic, hydrogeological factors, solar radiation and other climatic factors, geometrical parameters of a road, etc. Considering the non-rigid pavement, it should be noted that the influence of temperature is very significant too. Indeed, with the considerable temperature fluctuations changes occur within the physical and mechanical properties of asphalt and other road-building materials with an organic binder [Teltaev, 2007]. It may cause the appearance of damages in a pavement.

The most common type of asphalt pavement damage is cracks of different nature, size, and location. Researchers are constantly offering new constructive measures to prevent the formation of cracks and repair of already formed temperature, reflection or technological cracks [Blazejowski, Styk, 2004]. However, theoretical studies using modern calculation methods make it possible to accurately determine the genesis of cracks in the pavement in order to make the right decisions in the design and repairing of road structures that enhance their durability.

2. The choice of design schemes to estimate crack resistance of road structures under the influence of temperature and traffic load

Cracks usually appear under tensile or bending stresses in pavement layers under the action of traffic loads and temperature fluctuations, and especially in their combined action. Thermal cracks initiated at the top of an asphalt layer and grow from the top to bottom, as the crack in the bend zone of the pavement under the wheel load. Reflected cracks grow up from the bottom: from the crack of and old lower asphalt concrete layer or a joint of cement concrete slab [Vasiliyev, 2004]. It is assumed that the cracks are formed in asphalt concrete layer when tensile stresses exceed the tensile strength of asphalt concrete.

For theoretical studies of the road structure mode of deformation the finite element method (FEM) should be applied as a calculation method [Elsefi, 2003]. This paper presents a model of pavement made in the analytical design system SolidWorks.

The geometric model of the considered structure has five layers: two layers of pavement (a dense asphalt concrete layer 2.5 cm thick and a porous asphalt concrete layer 7–10 cm thick) and three base layers (gravel 20–50 cm thick, sand 30–60 cm thick, soil base not less than 80 cm thick).

The database of road-building materials properties allows us to define the values of the next physical and mechanical parameters: modulus of elasticity, mass density, Poisson’s ratio, thermal conductivity, specific heat capacity, coefficient of thermal expansion, tensile strength, compressive strength. Moreover, values of the modulus of elasticity, density, tensile strength and compressive strength of asphalt concrete, sand and gravel depending on the temperature are also taken into account when setting the properties of the materials to calculate the mode of deformation of the structure [Melnikova, 2012].

Geometry of the three-dimensional pavement model is as follows: every layer is a box 900 by 900 mm to avoid the influence of the edge effect. The thickness of the structural layers may vary.

Traffic impact on the road surface has been modeled as a wheel load from a heavy truck KAMAZ-65117 which has the load of 115 kN per axle. This load has been modeled as a pressure of 0.43 MPa to the rectangular area 28 by 23.8 mm.

The initial conditions for air temperature effect estimation are as follows: geographical location – Minsk (53.89 deg. latitude), season – winter, January, air temperatures were taken according to data of The Republican Hydro meteorological Center for Minsk. Surface temperatures were taken in accordance with the obtained mathematical relation between air and surface temperatures. The formula was obtained by statistical analysis of measurement data from the road measurement stations provided by Belarusian Road Engineering and Technology Center [Leonovich, Melnikova, 2012].

Several analytical models of pavements were considered to predict the mode of deformation using FEM [Zholobov, 2000]. Design models reflected the work of a pavement before cracking, after temperature or reflective cracking, as well as before/after the repair activities of different kinds. Furthermore two base types were taken into consideration: solid (discrete) which does not result in pavement deformation and cracked slab causing additional horizontal deformation of the pavement due to an adhesion with the base (old cracked asphalt concrete layer, concrete slabs) under cyclic deformation.

Design models for estimation of pavement crack resistance before cracking as well as the connection between pavement layers and adjacent sections (hinged movable support), between asphalt layers and lower construction layers (hinged-fixed support) are shown in Figure 1.

Figure 1a shows the asphalt surface layer without cracks on solid base at the beginning of road service period. Figure 1b presents a design model when the top asphalt layer is laid directly on the cracked asphalt basis or cement slab with joints (crack-interrupting layer is absent). Model 1c takes into account crack-interrupting layer arranged in the lower area of the upper asphalt concrete layer over the existing cracks in asphalt base or joint in concrete slab.

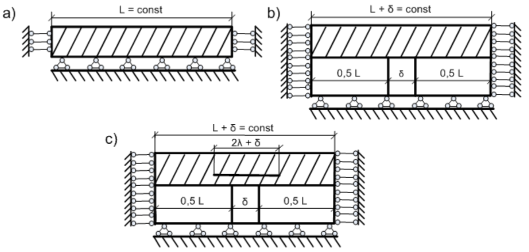


Fig. 1. Design models for the calculation of stresses in asphalt concrete pavement before cracking:
a – on a solid basis; b – on a cracked basis; c – on a cracked basis with a crack-interrupting layer;
L – length of the considering pavement fragment;
δ – joint width in concrete slabs or width of the existing crack in asphalt base layer

In all three cases it is assumed that the length of the considering pavement fragment remains the same. The base of the pavement for modeling consists of 3 layers:

- fractionated gravel layer;
- medium size sand layer;
- clay loam layer as a pavement basis.

Design models for estimation of pavement crack resistance after cracks appearance are shown in Figure 2. Figure 2a presents the process of thermal cracking in the upper zone of asphalt layer due to the appearance of maximum tensile stress in the zone as a result of temperature and traffic load. Figure 2b shows the development of reflected cracks at some distance from the existing cracks in the lower asphalt layer or joints in concrete slabs.

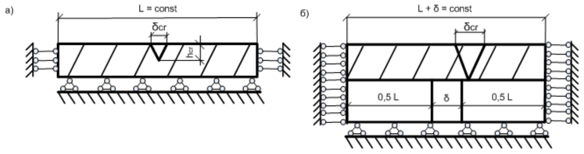


Fig. 2. Design models for the calculation of stresses in asphalt concrete pavement after crack appearance:
a – with thermal cracks in the upper zone of the asphalt pavement on a solid base; b – with reflected cracks in asphalt layer on a cracked base

Different pavement repair technologies are taken into consideration in design models from Figure 3 [Verenko, 2008]. Scheme 3a presents small cracks (0.5–0.7 cm width) repair method: filling a crack with a sealant (emulsified asphalt, liquid bitumen) followed by crack powdering with friction material without making a protective asphalt concrete layer. Pavement after its milling (width Δ =10–20 mm, 10–40 mm depth) and sealing the crack is shown in Figure 3b; width-to-depth ratio is taken 1:1 if crack width is up to 25 mm and width-to-depth ratio is taken 1:2 if crack width is more than 25 mm. Figures 3c and 3d correspond to asphalt pavement on a cracked basis crack sealing without/with milling. Crack sealing in asphalt concrete pavement on a cracked base when applying a wearing layer is presented in Figure 3e, the same thing with an additional applying of crack-interrupting layer of geosynthetic material 10–50 cm width – in Figure 3f [Górszczyk, 2004].

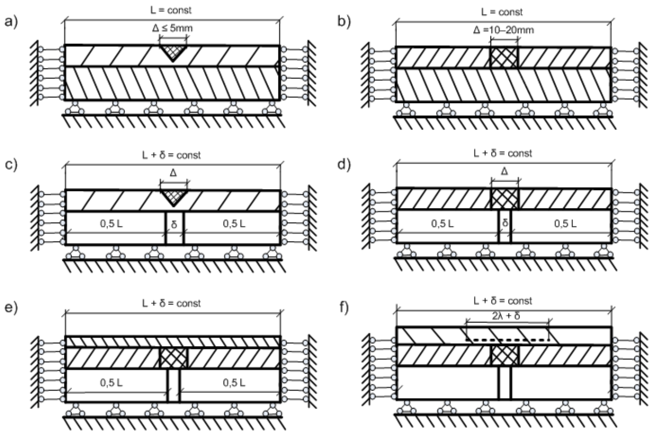


Fig. 3. Design models for the calculation of stresses in asphalt concrete pavement after repairing activities: a – after sealing cracks of a small width in the top layer of asphalt concrete pavement on a solid base; b – after milling and sealing a crack in asphalt concrete layer on a solid basis; c – after sealing cracks in asphalt concrete layer on a cracked basis; d – after milling and sealing cracks in asphalt concrete layer on a cracked basis; e – after milling, sealing cracks and applying of a wearing layer; f – after milling, sealing cracks, applying of a crack-interrupting layer and a wearing layer

Formation of thermal and reflected cracks may also take place after the repair. These design models are presented in Figure 4. The formation of cracks in the upper zone of the asphalt layer over the crack-interrupting layer is shown in Figure 4a. The crack formation in a sealant material is shown in Figure 4b.

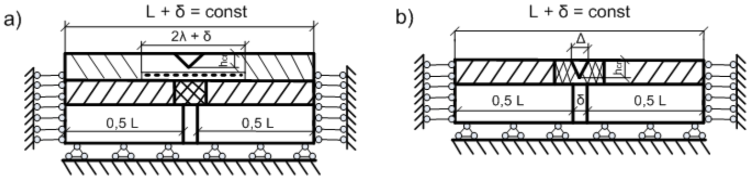


Fig. 4. Design models for the calculation of stresses in asphalt concrete pavement after the repair and re-crack formation: a – after applying of a crack-interrupting layer and a wearing layer; b – after crack formation in a sealant material

Further researches were related to learning of the pavement models mode of deformation to reveal shortcomings in the road pavement designing (selection of materials, their properties, later thickness, etc.), structure itself and choice of repair activities.

3. Modeling of the temperature and traffic load impact on the road structure

For the modeling of the temperature and traffic load impact some physical and mechanical properties of the materials were set according to the mean values, but properties of the upper layer's asphalt concrete were defined experimentally in order to obtain the most reliable modeling results. Modulus of elasticity and tensile strength of asphalt concrete were defined after the testing of beams (4x4x12 cm) on elastic supports at three different temperatures (–20 ºC, 0 ºC, +20 ºC) using the dynamic load press (central point load). Thermal conductivity was defined by laboratory tests on the HFM 436/3/1E Lambda^{TM} device.

Pavement structures for simulation were chosen according to the requirements of the normative documents of the Republic of Belarus. Design models are corresponding to the schemes presented above in Figures 1–4 and detailed information is in Table 1.

Thermal and traffic loads:

a – wheel load: was modeled as a quarter of a tire print and a pressure of 0.43 MPa (Fig. 5);

b – thermal load: –20 ºC;

c – the simultaneous impact of temperature and transport: –20 ºC and the wheel load;

d – three of the coldest days of the year: for Minsk, from 6 p.m. of the 22-th of January to 6 p.m. of the 24-th of January 2011;

e – three of the warmest days of the year: for Minsk, from 6 p.m. of the 23-th of August to 6 p.m. of the 25-th of August 2011.

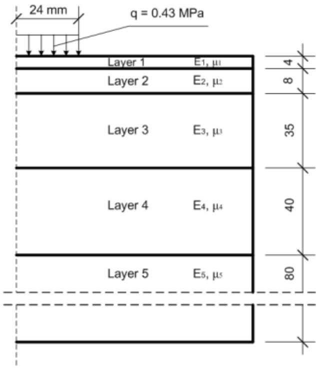


Fig. 5. Pavement structure model adopted for the calculations

The modeling results are represented below. Calculations of compressive stress, tensile stress and deflection were carried out using finite element method.

Table 1. Road structure of modeled schemes (presented in Figures 1–4)

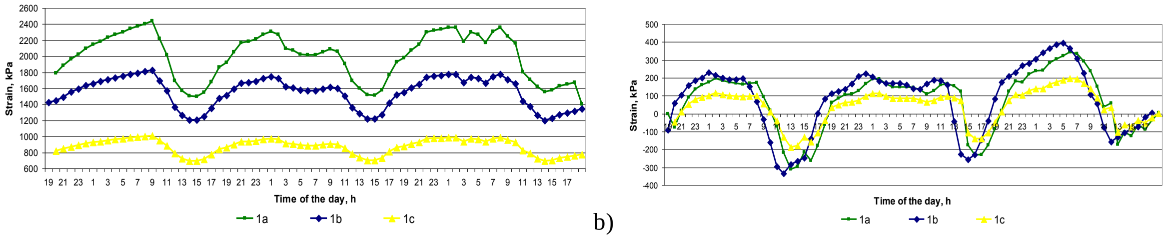
Layer	Layer thickness, cm												
	Schemes:												
	1a	1b	1c	2a	2b	3a	3b	3c	3d	3e	3f	4a	4b
Wearing layer (dense asphalt concrete)	-	-	-	-	-	-	-	-	-	2	2	-	-
Wearing layer (dense a/c) with a crack of 1 cm width and 1.6 cm depth	-	-	-	-	-	-	-	-	-	-	-	2	-
Dense asphalt concrete	4	4	4	-	-	-	-	-	-	-	-	-	-
Dense a/c with a crack of 1 cm width and 1.5 cm depth	-	-	-	4	-	-	-	-	-	-	-	-	-
Dense a/c with a crack of 1 cm width and 4 cm depth, 2 cm away from the base crack	-	-	-	-	4	-	-	-	-	-	-	-	-
Dense a/c with a crack of 0.5 cm width and 3 cm depth, filled with sealant (liquid bitumen)	-	-	-	-	-	4	-	4	-	-	-	-	4
Dense a/c with a crack of 2 cm width and 4 cm depth after milling, filled with sealant (liquid bitumen)	-	-	-	-	-	-	4	-	4	4	4	4	-
Geotextile Dornit	-	-	0.4	-	-	-	-	-	-	-	0.4	0.4	-
Porous asphalt concrete	8	-	-	8	-	8	8	-	-	-	-	-	-
Porous a/c with a crack of 1 cm width	-	8	8	-	8	-	-	8	8	8	8	8	8
Gravel	35	35	35	35	35	35	35	35	35	35	35	35	35
Sand	40	40	40	40	40	40	40	40	40	40	40	40	40
Silty clay loam (base layer)	80	80	80	80	80	80	80	80	80	80	80	80	80

Research results of the mode of deformation for schemes 1a–1c are presented in Table 2 (layer 1 is a dense asphalt concrete, layer 2 – porous asphalt concrete). Stresses in asphalt concrete upper layer under the thermal load for three coldest and warmest days are presented in Figure 6. Fig 6a presents stresses during the days with maximum negative temperatures, Fig 6b – with maximum positive temperatures.

Table 2. Results of the mode of deformation research for schemes 1a–1c

Model number, load	Layer number	Maximum compressive stress, MPa	Maximum tensile stress, MPa	Deflection, mm
1a: load a	1	0,4919	0,0569	0,1985
	2	0,2296	0,0776	
1a: load b	1	0,8327	2,3499	-
	2	0,8327	0,0604	
1a: load c	1	0,8361	2,3146	0,2226
	2	0,8361	0,0614	
1b: load a	1	0,4578	0,0382	0,2349
	2	0,2316	0,0859	
1b: load b	1	0,8876	3,0844	-
	2	0,1099	0,0592	

1b: load c	1	1,1461	3,0381	0,2394
	2	0,2529	0,0507	
1c: load a	1	0,5003	0,0340	0,1952
	2	0,3483	0,0841	
1c: load b	1	0,4268	2,3385	-
	2	0,4268	0,0886	
1c: load c	1	0,8558	1,7498	0,2148
	2	0,4152	0,0846	



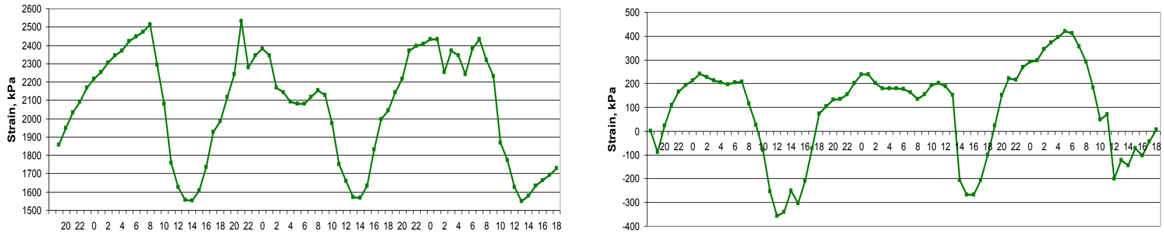
a) b)

Fig. 6. Mode of deformation for the upper asphalt concrete layer (schemes 1a–1c)

The calculation results for scheme 3b are identical to the scheme 2a results [Dave, 2007]. Research results of the mode of deformation are presented in Table 3 (layer 1 is a dense asphalt concrete, layer 2 – porous asphalt concrete). Stresses in asphalt concrete upper layer (dense asphalt concrete) under the thermal load for three coldest and warmest days are presented in Figure 7. Fig 7a presents stresses during the days with maximum negative temperatures, Fig 7b – with maximum positive temperatures.

Table 3. Results of the mode of deformation research for scheme 2a

Model number, load	Layer	Maximum compressive stress, MPa	Maximum tensile stress, MPa	Deflection, mm
2a: load a	1	0,2264	0,0744	0,0535
	2	0,0784	0,0909	
2a: load b	1	0,6071	2,4933	-
	2	0,6071	0,0754	
2a: load c	1	0,6830	2,4603	0,0566
	2	0,6830	0,0118	



a) b)

Fig. 7. Mode of deformation for the upper asphalt concrete layer (scheme 2a)

The calculation results for scheme 3c are identical to the scheme 3a results. Research results of the mode of deformation for schemes 3a–3d are presented in Table 4 (layer 1 is a dense asphalt concrete, layer 2 – porous asphalt concrete, layer 3 – sealant).

Table 4. Results of the mode of deformation research for schemes 3a–3d

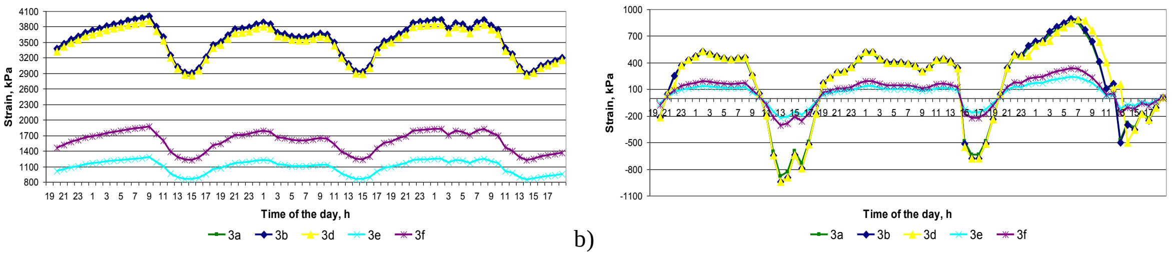
Model number, load	Layer	Maximum compressive stress, MPa	Maximum tensile stress, MPa	Deflection, mm
3a: load a	1	0,5677	0,0625	0,2058
	2	0,3287	0,0405	
3a: load b	1	0,8311	4,6493	-
	2	1,1160	0,2933	
3a: load c	1	1,4566	4,3901	0,1815
	2	1,3417	0,0916	
3b: load a	1	0,4495	0,0442	0,2329
	2	0,2637	0,0694	

	3	0,3603	0,0158	
3b: load b	1	1,9450	3,8694	-
	2	0,5743	0,0111	
	3	1,9450	5,5593	
3b: load c	1	2,0001	3,8794	0,3409
	2	0,6542	0,0110	
	3	2,0001	5,5582	
3d: load a	1	0,4321	0,0575	0,2354
	2	0,3000	0,0491	
	3	0,3779	0,0163	
3d: load b	1	0,9367	4,2712	-
	2	2,9491	0,0984	
	3	2,9491	5,3770	
3d: load c	1	1,2849	4,2766	0,3792
	2	2,9503	0,0983	
	3	2,9503	5,3676	

Research results of the mode of deformation for schemes 3e–3f are presented in Table 5 (layer 1 is dense asphalt concrete, layer 2 – porous asphalt concrete, layer 3 – sealant, layer 4 – a wearing layer, layer 5 – geotextile layer). Stresses in asphalt concrete upper layer under the thermal load for three coldest and warmest days are presented in Figure 8. Fig 8a presents stresses during the days with maximum negative temperatures, Fig 8b – with maximum positive temperatures.

Table 5. Results of the mode of deformation research for schemes 3e–3f

Model number, load	Layer	Maximum compressive stress, MPa	Maximum tensile stress, MPa	Deflection, mm
3e: load a	1	0,3725	-	0,1956
	2	0,1833	0,0485	
	3	0,2826	0,0143	
	4	0,5183	0,0392	
3e: load b	1	1,0737	0,0660	-
	2	0,0532	0,0145	
	3	1,1288	0,0169	
	4	1,1288	2,9483	
3e: load c	1	1,0771	0,0613	0,2048
	2	0,2178	0,0145	
	3	1,1212	0,0168	
	4	1,1212	2,9528	
3f: load a	1	0,5635	-	0,1929
	2	0,1829	0,0654	
	3	0,4273	0,0148	
	4	0,5594	0,0244	
	5	0,7216	-	
3f: load b	1	0,7599	0,0319	-
	2	0,0519	0,0165	
	3	1,0406	0,0159	
	4	1,0406	3,0874	
	5	0,3052	0,0630	
3f: load c	1	0,7326	-	0,1985
	2	0,1999	0,0353	
	3	1,0361	0,0098	
	4	1,0361	3,0967	
	5	0,6926	-	



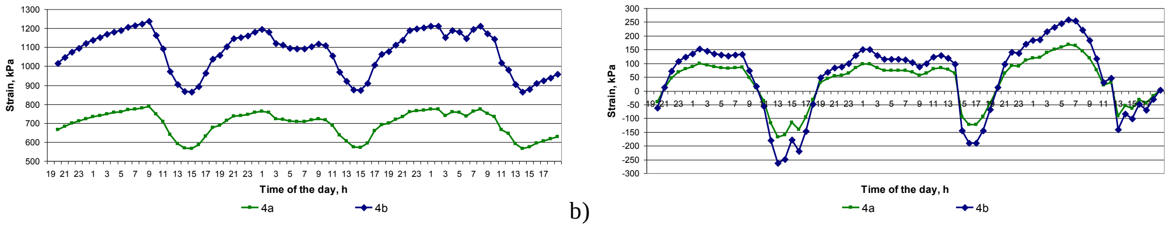
a) b)

Fig. 8. Mode of deformation for the upper asphalt concrete layer (schemes 3a–3b, 3d–3f)

Research results of the mode of deformation for schemes 4a–4b are presented in Table 6 (layer 1 is dense asphalt concrete, layer 2 – porous asphalt concrete, layer 3 – sealant, layer 4 – a wearing layer, layer 5 – geotextile layer). Stresses in asphalt concrete upper layer under the thermal load for three coldest and warmest days are presented in Figure 9. Fig 9a presents stresses during the days with maximum negative temperatures, Fig 9b – with maximum positive temperatures.

Table 6. Results of the mode of deformation research for schemes 4a–4b

Model number,	Layer	Maximum compressive stress, MPa	Maximum tensile stress, MPa	Deflection, mm
4a: load a	1	0,2864	0,7329	0,0797
	2	0,0717	0,0397	
	3	2,4020	0,7329	
	4	2,4020	0,2555	
	5	2,3812	1,1252	
4a: load b	1	0,1950	0,0727	-
	2	0,0458	0,0295	
	3	0,2538	0,2407	
	4	0,4474	2,4000	
	5	0,2085	0,0727	
4a: load c	1	0,3169	0,6360	0,0835
	2	0,0962	0,0294	
	3	2,3292	0,6360	
	4	2,3292	2,4056	
	5	2,3011	0,9173	
4b: load a	1	0,2747	0,0461	0,1974
	2	0,2161	0,0414	
	3	0,5833	0,0315	
4b: load b	1	1,9538	2,5399	-
	2	0,7943	0,1496	
	3	1,9802	4,9736	
4b: load c	1	2,0500	2,5664	0,1479
	2	0,8881	0,1465	
	3	2,1536	4,9894	



a) b)

Fig. 9. Mode of deformation for the upper asphalt concrete layer (schemes 4a–4b)

Key simulation findings are presented below. It is recommendations about how to improve crack resistance of asphalt concrete pavements.

1) Road structures with a thickness of asphalt pavement of at least 10–12 cm are less exposed to cracking in the climatic conditions of the Republic of Belarus. Pavements with less than 10 cm thickness are not resistant enough to thermal cracking.

2) Modulus of elasticity of the upper layer material (asphalt concrete) should be small at low temperatures below zero.

3) Material for a membrane type crack-interrupting layer should have the smallest modulus of elasticity as it is inexpedient to apply these layer in case of a close modulus of elasticity values of pavement materials and membrane type layer itself.

4) The using of a geosynthetic material as a crack-interrupting layer and as a repairing material allows us to reduce the resulting tensile stresses in the top layer of a pavement, but only if it was laying in the bottom zone of the pavement. It is allowed to make a reinforcement of the top pavement zone with geosynthetics with an additional apply of surface treatment or wearing layer 2–3 cm thick.

5) The most effective measures of crack repairing are: milling and sealing the cracks with a wearing layer construction; sealing the cracks with a crack-interrupting geosynthetic layer construction over the crack with a wearing layer (dense asphalt concrete).

Further research will focus on a more detailed study of road structures using FEM. It will allow us to substantiate the using of the materials, choice of layers thicknesses, etc., to increase crack resistance of asphalt concrete pavements.

4. Conclusions

1. Crack resistance of road constructions could be increased if design decisions will be made on the basis of the theoretical research base. It is possible today because a large amount of calculations of temperature and traffic impact on a pavement could be done using FEM.

2. Recommendations to improve crack resistance of asphalt concrete pavements in the load conditions of the Republic of Belarus were made as a result of the modeling process. First of all there are recommendations on the choice of pavement layer thickness, physical and mechanical properties of construction materials, material type to make a crack-interrupting layer, on the choice of a repair activity to repair the cracks in the top pavement layer effectively. These recommendations should also be considered when designing flexible pavements, its maintenance and planning of the current and capital repairs of the republican roads.

References

Blazejowski K., Styk S. 2004. *Technologia warstw asfaltowych* [Technology of asphalt layers], *Wydawnictwa komunikacji i lacznosci*. 408 p. ISBN 9788320615401

Dave, E. 2007. Reflective and thermal cracking modeling of asphalt concrete overlays, in *International conference of advanced characterization of pavement and soil engineering materials*: Selected papers, vol. 1. Ed. By A. Loizos, T. Scarpas, I. Al-Qadi. June 20–22, 2007, Athens, Greece. Athens: Taylor & Francis, 1241–1252.

Elsefi, M. A. 2003. Performance quantification of interlayer systems in flexible pavements using finite element analysis, instrument response, and non destructive testing. Virginia: Virginia Polytechnic Institute and State University, 429 p.

Górszczyk, J. 2004. Modeling of asphalt pavement structure with geosynthetics interlayer using of finite element method, in *The 10th International conference "Durable and safe road pavements"*: Selected papers. May 11–12, 2004, Kielce, Poland, p. 271–278.

Васильев, А. 2004. *Справочная энциклопедия дорожника* [Vasiliyev, A. Encyclopedia for a road worker], Москва: Информавтодор. 507 с. (in Russian)

Веренько, В. 2008. *Деформации и разрушения дорожных покрытий: причины и пути устранения* [Verenko, V. Deformation and destructions of road pavements: the reasons and ways of elimination]. Минск: Беларуская Энцыклапедыя імя Броукі. 304 с. (in Russian)

Жолобов, А. 2000. *Прогнозирование поведения технологических систем на стадии их проектирования* [Zholobov, A.; Popkovsky V.; Popkovsky D. Prediction of technological systems behavior at the design stage]. Могилев: МГТУ. 150 с. (in Russian)

Мельникова, И. 2012. Моделирование воздействия температуры и транспортных нагрузок на возникновения и развитие трещин в асфальтобетонных дорожных покрытиях [Melnikova, I.], *Наука и техника* [The Science and Technology] 4: 44–52. (in Russian)

Леонович, И.; Мельникова, И. 2012. Инновации в системе эксплуатации автомобильных дорог, направленные на предупреждение и ликвидацию поверхностных дефектов [Leonovich, I; Melnikova, I.], *Труды БГТУ* [Trudy BGTU] 2 (149): 130–133. (in Russian)

Телтаев, Б. 2007. Прогноз температурного режима дорожной конструкции методом конечных элементов [Teltaev, B. Road structure temperature schedule prognosis using finite element method], *Наука и техника в дорожной отрасли* [The Science and technics in road branch] 2: 18–21. (in Russian)

Received 21 December 2012; accepted