



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

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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. According to the modeling results appearance of reflected cracks under the traffic load and cracks that occurred under the influence of temperature were predicted. 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 10 000 km² 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 carried out nowadays. Furthermore, as the Republic of Belarus is a transit country, road service is working on increasing the road capacity up to 13 t/axle.

Durability of the road structure is one of the most important parameters of technical and operating conditions 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 repair 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 are 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 5 layers: 2 layers of pavement (a dense asphalt concrete layer 2.5 cm thick and a porous asphalt concrete layer 7–10 cm

thick) and 3 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 defining 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 900×900 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/axle. This load has been modeled as a pressure of 0.43 MPa to the rectangular area 28×23.8 mm.

The initial conditions for air temperature effect estimation are as follows: geographical location – Minsk (53.89° 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 Figs 1–3.

Fig. 1 shows the asphalt surface layer without cracks on solid base at the beginning of road service period. Fig. 2 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 in Fig. 3 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. In Figs 1–3 L – length of the considered pavement fragment

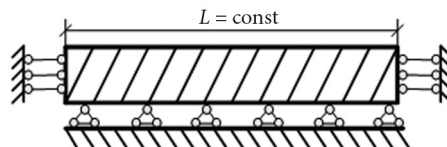


Fig. 1. Design model for the calculation of stresses in asphalt concrete pavement before cracking on a solid basis

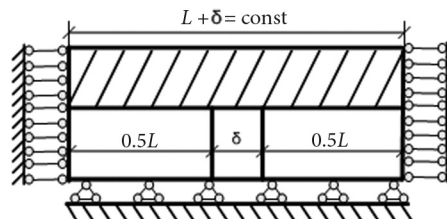


Fig. 2. Design models for the calculation of stresses in asphalt concrete pavement before cracking on a cracked basis

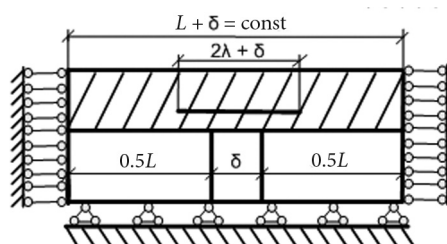


Fig. 3. Design models for the calculation of stresses in asphalt concrete pavement before cracking on a cracked basis with a crack-interrupting layer

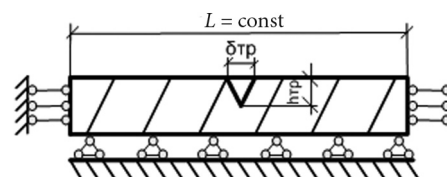


Fig. 4. Design model for the calculation of stresses in asphalt concrete pavement after crack appearance with thermal cracks in the upper zone of the asphalt pavement on a solid basis

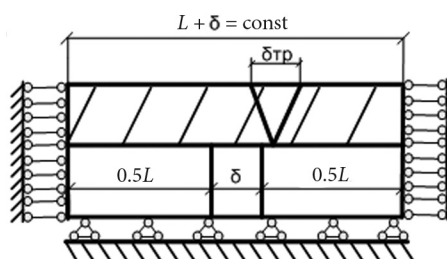


Fig. 5. Design model for the calculation of stresses in asphalt concrete pavement after crack appearance with reflected cracks in asphalt layer on a cracked base

and δ – joint width in concrete slabs or width of the existing crack in asphalt base layer.

In all 3 cases (Figs 1–3) it is assumed that the length of the considered 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 Figs 4 and 5. Fig. 4 presents the process of thermal cracking in the upper zone of asphalt layer due to the appearance of max tensile stress in the zone as a result of temperature and traffic load. Fig. 5 shows the development of reflected cracks at some distance from the existing cracks in the lower asphalt layer or joints in concrete slabs.

Different pavement repair technologies are taken into consideration in design models from Figs 6–11 (Verenko 2008). Fig. 6 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.

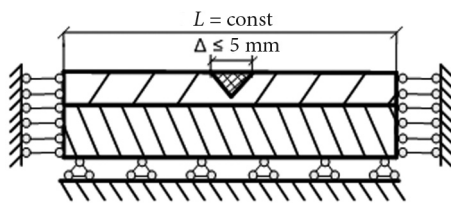


Fig. 6. Design model for the calculation of stresses in asphalt concrete pavement after repairing activities after sealing cracks of a small width in the top layer of asphalt concrete pavement on a solid base

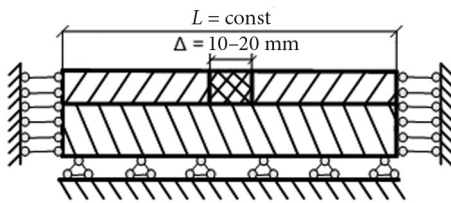


Fig. 7. Design model for the calculation of stresses in asphalt concrete pavement after repairing activities after milling and sealing a crack in asphalt concrete layer on a solid basis

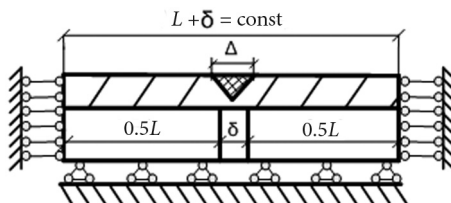


Fig. 8. Design model for the calculation of stresses in asphalt concrete pavement after repairing activities after sealing cracks in asphalt concrete layer on a cracked basis

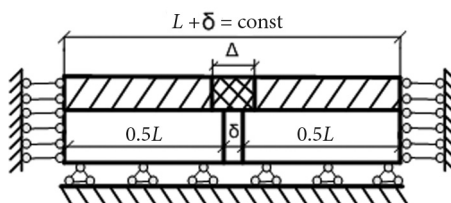


Fig. 9. Design model for the calculation of stresses in asphalt concrete pavement after repairing activities after milling and sealing cracks in asphalt concrete layer on a cracked basis

Pavement after its milling (width $\Delta = 10\text{--}20$ mm, $10\text{--}40$ mm depth) and sealing the crack is shown in Fig. 7; 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. Figs 8 and 9 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 Fig. 10, the same thing with an additional application of crack-interrupting layer of geosynthetic material 10–50 cm width – in Fig. 11 (Górszczyk 2004).

Formation of thermal and reflected cracks may also take place after the repair. These design models are presented in Figs 12 and 13. The formation of cracks in the upper

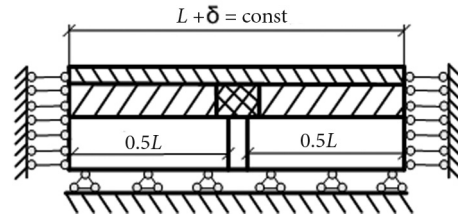


Fig. 10. Design model for the calculation of stresses in asphalt concrete pavement after repairing activities after milling, sealing cracks and applying of a wearing layer

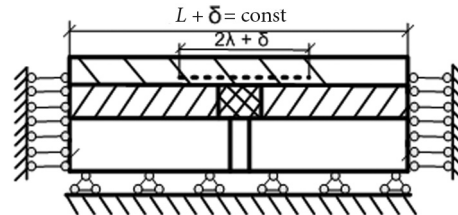


Fig. 11. Design model for the calculation of stresses in asphalt concrete pavement after repairing activities after milling, sealing cracks, applying of a crack-interrupting layer and a wearing layer

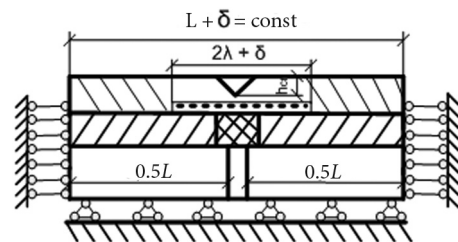


Fig. 12. Design model for the calculation of stresses in asphalt concrete pavement after the repair and re-crack formation after applying of a crack-interrupting layer and a wearing layer

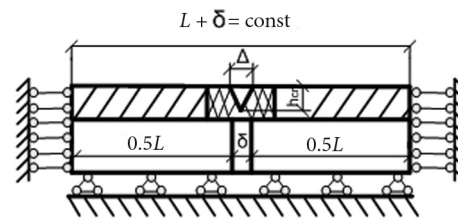


Fig. 13. Design model for the calculation of stresses in asphalt concrete pavement after the repair and re-crack formation after crack formation in a sealant material

Table 2. Results of the mode of deformation research (Figs 1–3)

Model number: load	Layer number	Max compressive stress, MPa		Max tensile stress, MPa		Deflection, mm
Fig. 1: load a	1	0.4919		0.0569		0.1985
	2	0.2296		0.0776		
Fig. 1: load b	1	0.8327		2.3499		–
	2	0.8327		0.0604		
Fig. 1: load c	1	0.8361		2.3146		0.2226
	2	0.8361		0.0614		
Fig. 2: load a	1	0.4578		0.0382		0.2349
	2	0.2316		0.0859		
Fig. 2: load b	1	0.8876		3.0844		–
	2	0.1099		0.0592		
Fig. 2: load c	1	1.1461		3.0381		0.2394
	2	0.2529		0.0507		
Fig. 3: load a	1	0.5003		0.0340		0.1952
	2	0.3483		0.0841		
Fig. 3: load b	1	0.4268		2.3385		–
	2	0.4268		0.0886		
Fig. 3: load c	1	0.8558		1.7498		0.2148
	2	0.4152		0.0846		

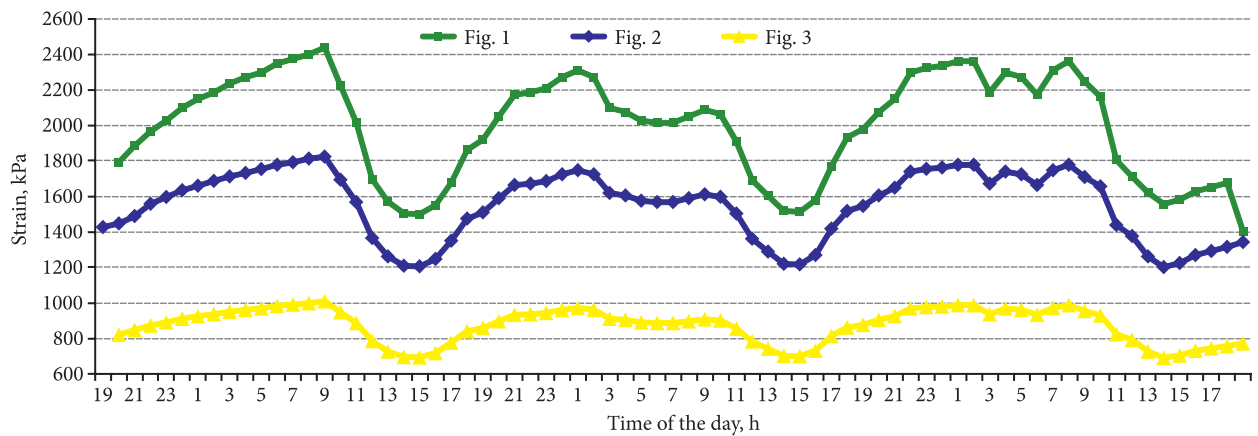


Fig. 15. Mode of deformation for the upper asphalt concrete layer – stresses during the days with max negative temperatures (schemes in Figs 1–4)

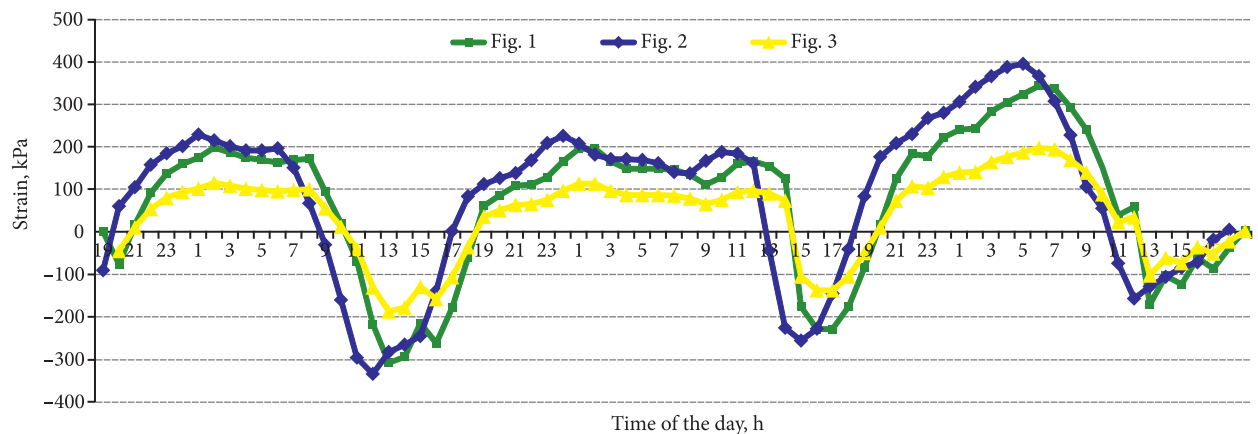


Fig. 16. Mode of deformation for the upper asphalt concrete layer – stresses during the days with max positive temperatures (schemes in Figs 1–4)

Table 3. Results of the mode of deformation research for scheme in Fig. 4

Model number: load	Layer number	Max compressive stress,	Max tensile stress,	Deflection, mm
		MPa		
Fig. 4: load a	1	0.2264	0.0744	0.0535
	2	0.0784	0.0909	
Fig. 4: load b	1	0.6071	2.4933	–
	2	0.6071	0.0754	
Fig. 4: load c	1	0.6830	2.4603	0.0566
	2	0.6830	0.0118	

presents stresses during the days with max negative temperatures, Fig. 16 – with max positive temperatures.

The calculation results for the scheme in Fig. 5 are identical to the results of the scheme in Fig. 4 (Dave 2007). Research results of the mode of deformation are presented in Table 3 (layer 1 is dense asphalt concrete, layer 2 – porous asphalt concrete). Stresses in asphalt concrete upper layer (dense asphalt concrete) under the thermal load for 3 coldest and warmest days are presented in Fig. Figs 17 and 18. Fig. 17 presents stresses during the days with max negative temperatures, Fig. 18 – with max positive temperatures.

The calculation results for the scheme in Fig. 8 are identical to the results of the scheme in Fig. 6. Research results of the mode of deformation for schemes in Figs 6–9 are presented in Table 4 (layer 1 is dense asphalt concrete, layer 2 – porous asphalt concrete, layer 3 – sealant).

Research results of the mode of deformation for Figs 10 and 11 are presented in Table 5 (layer 1 is dense asphalt concrete, layer 2 – porous asphalt concrete, layer 3 – sealant, layer 4 – 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 Figs 19 and 20. Fig. 19 presents stresses during the days with max negative temperatures, Fig. 20 – with max positive temperatures.

Research results of the mode of deformation for Figs 12 and 13 are presented in Table 6 (layer 1 is dense asphalt concrete, layer 2 – porous asphalt concrete, layer 3 – sealant, layer 4 – 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 Figs 21 and 22. Fig. 21 presents stresses during the days with max negative temperatures, Fig. 22 – with max positive temperatures.

Key simulation findings are presented below. These are recommendations on how to improve crack resistance of asphalt concrete pavements.

1) Road structures with the 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 enough resistant to thermal cracking.

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

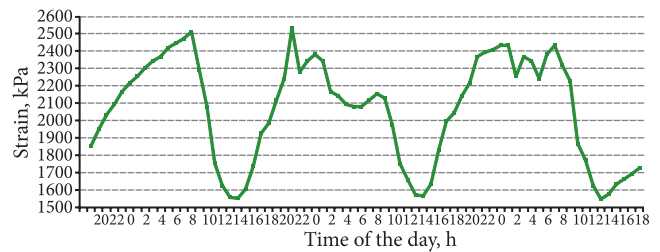


Fig. 17. Mode of deformation for the upper asphalt concrete layer – stresses during the days with max negative temperatures (scheme in Fig. 4)

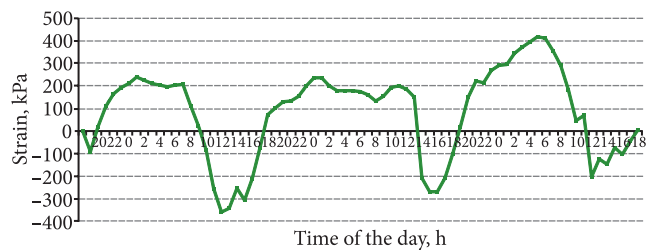


Fig. 18. Mode of deformation for the upper asphalt concrete layer – stresses during the days max positive temperatures (scheme in Fig. 4)

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 use of a geosynthetic material as a crack-interrupting layer and as repair material allows to reduce the resulting tensile stresses in the top layer of a pavement, but only if it was laid 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 repair 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 to substantiate the use of materials, choice of layers thicknesses, etc., to increase crack resistance of asphalt concrete pavements.

Table 4. Results of the mode of deformation research for schemes in Figs 6–9

Model number load	Layer number	Max compressive stress		Max tensile stress	Deflection, mm
		MPa			
Fig. 6: load a	1	0.5677		0.0625	0.2058
	2	0.3287		0.0405	
Fig. 6: load b	1	0.8311		4.6493	–
	2	1.1160		0.2933	
Fig. 6: load c	1	1.4566		4.3901	0.1815
	2	1.3417		0.0916	
Fig. 7: load a	1	0.4495		0.0442	0.2329
	2	0.2637		0.0694	
	3	0.3603		0.0158	
Fig. 7: load b	1	1.9450		3.8694	–
	2	0.5743		0.0111	
	3	1.9450		5.5593	
Fig. 7: load c	1	2.0001		3.8794	0.3409
	2	0.6542		0.0110	
	3	2.0001		5.5582	
Fig. 9: load a	1	0.4321		0.0575	0.2354
	2	0.3000		0.0491	
	3	0.3779		0.0163	
Fig. 9: load b	1	0.9367		4.2712	–
	2	2.9491		0.0984	
	3	2.9491		5.3770	
Fig. 9: load c	1	1.2849		4.2766	0.3792
	2	2.9503		0.0983	
	3	2.9503		5.3676	

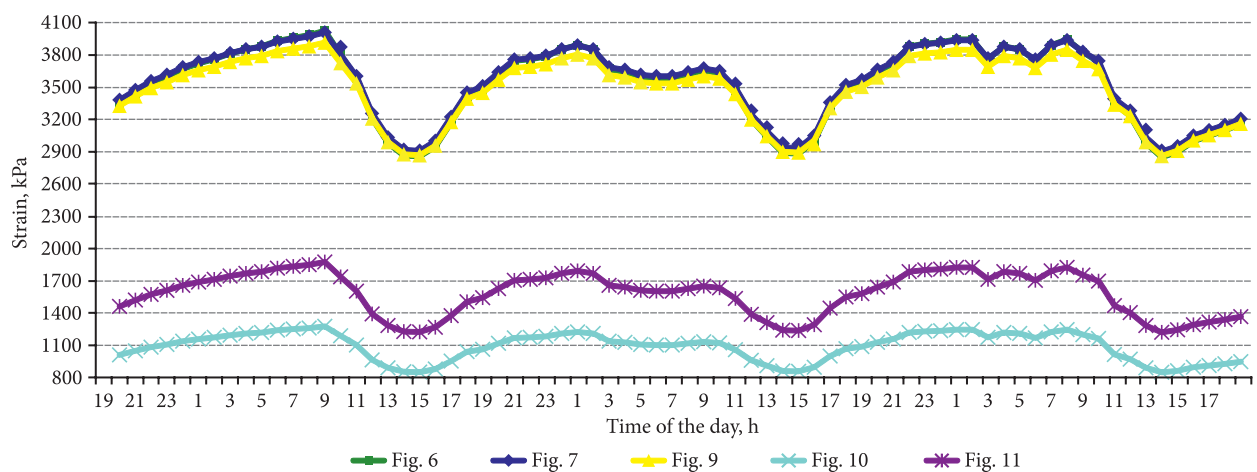


Fig. 19. Mode of deformation for the upper asphalt concrete layer – stresses during the days with max negative temperatures (schemes in Figs 6, 7, 9–11)

Table 5. Results of the mode of deformation research for schemes in Figs 10 and 11

Model number: load	Layer number	Max compressive stress, MPa		Max tensile stress, MPa		Deflection, mm
Fig. 10: load a	1	0.3725		–		0.1956
	2	0.1833		0.0485		
	3	0.2826		0.0143		
	4	0.5183		0.0392		
Fig. 10: load b	1	1.0737		0.0660		–
	2	0.0532		0.0145		
	3	1.1288		0.0169		
	4	1.1288		2.9483		
Fig. 10: load c	1	1.0771		0.0613		0.2048
	2	0.2178		0.0145		
	3	1.1212		0.0168		
	4	1.1212		2.9528		
Fig. 11: 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		–		
Fig. 11: 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		
Fig. 11: 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		–		

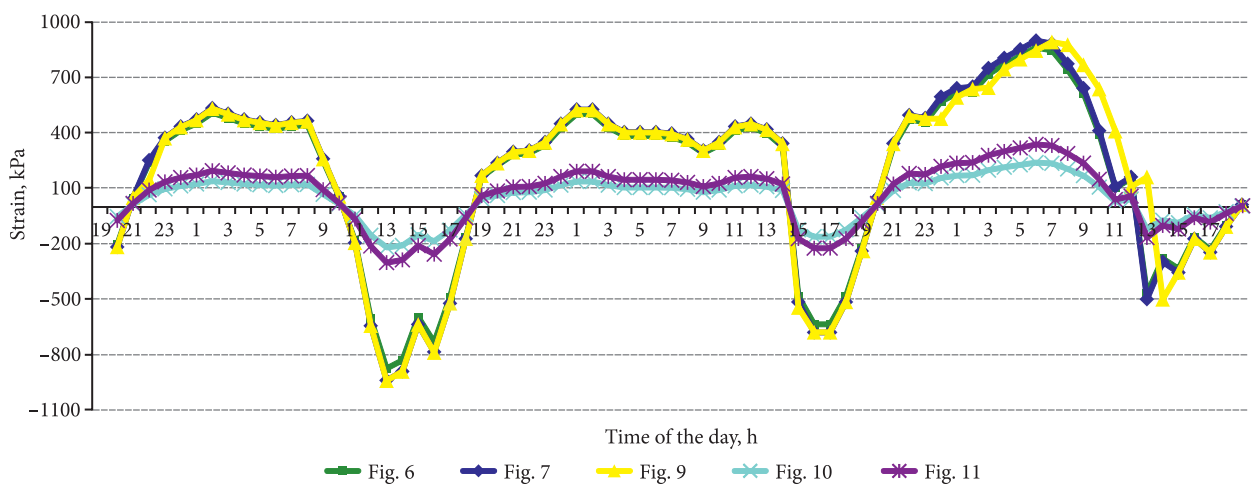


Fig. 20. Mode of deformation for the upper asphalt concrete layer – stresses during the days with max positive temperatures (schemes in Figs 6, 7, 9–11)

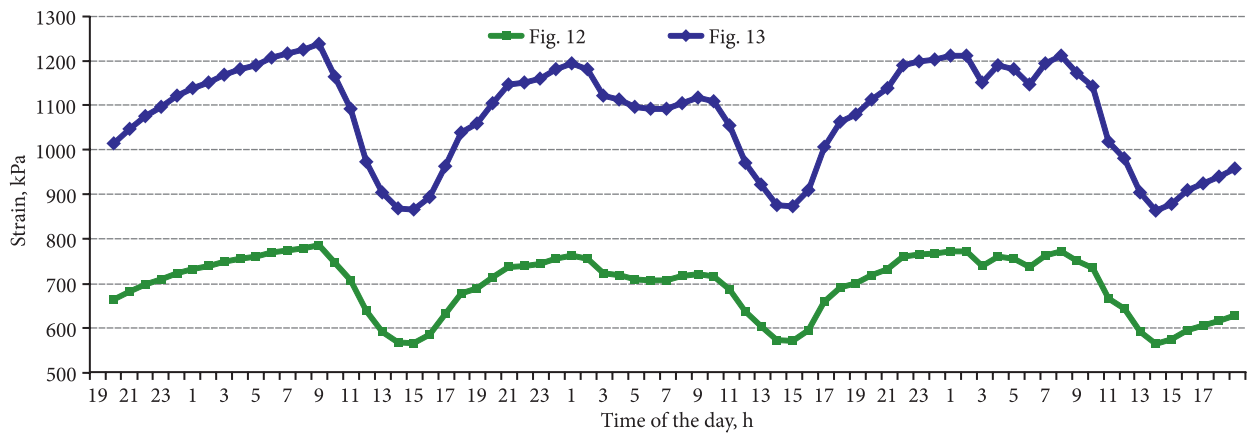


Fig. 21. Mode of deformation for the upper asphalt concrete layer presents stresses during the days with max negative temperatures (schemes in Figs 12 and 13)

Table 6. Results of the mode of deformation research for schemes in Figs 12 and 13

Model number, load	Layer number	Max stress, MPa		Deflection, mm
		Max compressive stress,	Max tensile stress,	
Fig. 12: 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	
Fig. 12: 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	
Fig. 12: 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	
Fig. 13: load a	1	0.2747	0.0461	0.1974
	2	0.2161	0.0414	
	3	0.5833	0.0315	
Fig. 13: load b	1	1.9538	2.5399	-
	2	0.7943	0.1496	
	3	1.9802	4.9736	
Fig. 13: load c	1	2.0500	2.5664	0.1479
	2	0.8881	0.1465	
	3	2.1536	4.9894	

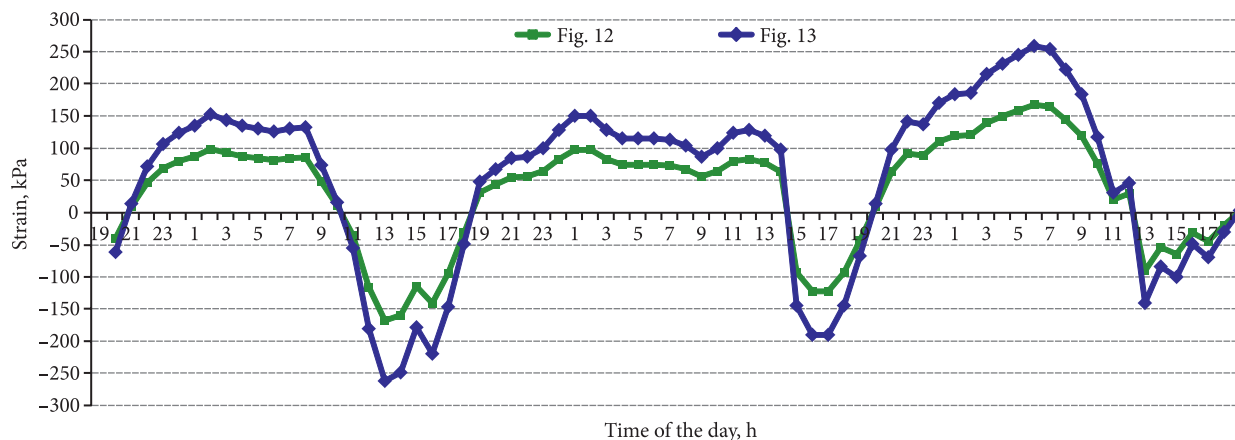


Fig. 22. Mode of deformation for the upper asphalt concrete layer presents stresses during the days with max positive temperatures (schemes in Figs 12 and 13)

4. Conclusions

1. If design decisions are made on the basis of the theoretical research base – crack resistance of road structures will be increased. It is possible today because a large amount of calculations of temperature and traffic impact on a pavement is 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.

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