METHOD OF ASSESSMENT OF NON-RIGID PAVEMENT RESISTANCE TO RUT FORMATION USING FINITE ELEMENT METHOD

МЕТОД ОЦІНКИ СТІЙКОСТІ ПОКРИТТЯ НЕЖОРСТКОГО ДОРОЖНЬОГО ОДЯГУ ДО УТВОРЕННЯ КОЛІЇ ЗА РАХУНОК МЕТОДУ СКІНЧЕННИХ ЕЛЕМЕНТІВ

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Abstract. The article shows the calculation of stress-strain state of asphalt pavement by finite element method using Ansys software system.

The object of the research is the displacements in the pavement design.

The aim of the research is to determine the resistance to rutting of asphalt concrete pavement of non-rigid road base.

Insufficient resistance of asphalt concrete pavement of roads and streets to rutting with the formation of shearing, shoving, rutting significantly reduces both the strength of the entire pavement design, and especially the level of traffic safety due to the effect of aqua-planing in places of stagnant water and winter slipperiness.

The results of the calculations make it possible theoretically to determine the rutting of asphalt concrete pavement based on a given number of vehicle passes and asphalt concrete pavement temperature.

Keywords: stress-strain state, rutting resistance, asphalt concrete pavement, residual strains.

Formulation of the problem. In recent years, one of the most common defects occurring in asphalt concrete pavement and reducing its service life is rutting.

Insufficient resistance of asphalt concrete pavement of roads and streets to rutting with the formation of shearing, shoving, rutting significantly reduces both the strength of the entire pavement design, and especially the level of traffic safety due to the effect of aqua-planing in places of stagnant water and winter slipperiness.

The rut formation significantly impairs the flatness of pavement, traffic comfort and adversely affects traffic safety, leads to rapid vehicle wear, increased fuel consumption, environmental degradation and increased cost of transportation.

When maintaining highways, rutting is one of the most dangerous types of deformation and destruction that significantly impair traffic safety [1]. According to the existing rules of repair and maintenance to highways of general use in Ukraine, the rutting on the maintained roadways is inadmissible, and the one that has emerged is subject to urgent liquidation [2].

The repair of rutting and other types of damages caused by their emerging require an additional increase in cost by an average of 200%. Therefore, due to the widespread and large volume of asphalt concrete pavements construction, as well as the significant unnecessary costs as a result of premature rutting, the issue of ensuring pavement resistance to rutting is relevant enough.

Thus, the simulation of the stress-strained state of non-rigid road base under a single load action by the finite element method is relevant for predicting rut formation of the pavement, taking into account the combined effect of the high temperature and the action of vehicles.

Research and publications analysis. The results of studies [3, 4] indicate that plastic deformations of asphalt concrete pavement are related to the number of load cycles, loading time, axle load, asphalt concrete properties, natural and climatic conditions.

The non-rigid pavement design sustains various types of static and dynamic impact from the loading of wheeled road transport, which leads to reversible and irreversible strain, the nature and magnitude of which define the service life [2, 4] of the highway.

The following studies [3, 5] consider in detail the issue of the occurrence of road construction deflections from road transport. Vertical deformations lead to the occurrence of stresses that penetrate the road structure to a considerable depth. The results of the study indicate that the stresses that have arisen on the surface of the pavement are determined, other conditions being equal, by the sum of the normal forces transmitted to the horizontal surface of the pavement by pneumatic wheels of a stationary motor vehicle.

The purpose of this article is to carry out the simulation of the stress-strain state of non-rigid road base by the finite element method for predicting residual strains.

Main part. To determine the displacements in the asphalt concrete pavement, in accordance with the design model and non-rigid pavement structures (Tables 1, 2), we performed the study of asphalt concrete pavement by the finite element method, according to the methodology given in the dependencies [6, 7], using Ansys software package.

We have carried out the simulation of the stress-strain state of these designs caused by the action of a stamp (circle with a radius of 16 cm) under pressure of 1 MPa, using finite element method in an axisymmetric and three-dimensional arrangement under different boundary conditions.

The non-rigid pavement designs with thicknesses of layers (for calculations we have selected the designs tested on the annular stand of DP «Dorcentr»), at different values of modules of elasticity at temperatures: +10 ° C; + 40 ° C; + 50 ° C; + 60 ° C is shown in the Tables 1, 2.

Axisymmetrical arrangement

The assumption of the symmetry of loading and boundary conditions allows us to consider this problem in an axisymmetrical arrangement. For this purpose, a circular cylinder with a diameter of 3 m, the center of the upper face of which sustains the pressure of 1 MPa, distributed in the middle of a circle with a radius of 16 cm (Fig. 1, 2). This arrangement allows you to simplify the simulation and reduce the number of finite elements.

Table 1 – The layer thicknesses of design No. 1 and their mechanical properties, depending on the temperature

Таблиця 1 – Товщина шарів конструкції №1 та їх механічні властивості залежно від температури

Layer of design	Name	Thickness h, cm	Modules of elasticity / Poisson's ratio			
			+10	+40	+50	+60
1	Dense asphalt concrete, fine-grained type B, grade I on bitumen modified by polymer BMP 60 / 90-52	5	4500 /0,3	690 /0,35	380 / 0,41	360 / 0,43
2	Dense asphalt concrete, coarse-grained type B, grade I on bitumen BND 60/90	10	3200 / 0,3	550 / 0,35	350 / 0,41	320 / 0,43
3	Porous asphalt concrete, coarse-grained, grade I.	10	2000 /0,3	460 /0,35	410 /0,41	340 /0,43
4	Macadam 20-40 mm	20	350 /0,27	350 /0,27	350 /0,27	350 /0,27
5	Sand	20	100 / 0,3	100 / 0,3	100 / 0,3	100 / 0,3
6	Subgrade soils – silt loam	235	77 / 0,35	77 / 0,35	77 / 0,35	77 / 0,35

Table 2 – The layer thicknesses of design No. 2 and their mechanical properties, depending on temperature

Таблиця 2 – Товщина шарів конструкції №2 та їх механічні властивості залежно від температури

Layer of design	Name	Thickness, h, cm	Modules of elasticity / Poisson's ratio			
			+10	+40	+50	+60
1	SMA-20 with bitumen, modified by the polymer BMP 60/90-52	5	3500 / 0,3	600 / 0,35	360 / 0,41	330 / 0,43
2	Dense asphalt concrete, coarse-grained (maximum grain size of mineral grains up to 20 mm), type A, grade I with bitumen BND 60/90	8	3200 / 0,3	550 / 0,35	350 / 0,41	320 / 0,43
3	Porous asphalt concrete, coarse-grained, grade I. fine-grained (maximum grain size of mineral grains up to 40 mm) of grade I	8	2000 / 0,3	460 / 0,35	410 / 0,41	340 / 0,43
4	Macadam-sand mixture C7, reinforced with cement M60	15	800 / 0,28	800 / 0,28	800 / 0,28	800 / 0,28
5	Macadam-sand mixture C5	18	260 / 0,3	260 / 0,3	260 / 0,3	260 / 0,3
6	Sand	20	100 / 0,3	100 / 0,3	100 / 0,3	100 / 0,3
7	Subgrade soils – loam	226	77 / 0,35	77 / 0,35	77 / 0,35	77 / 0,35

a) b)

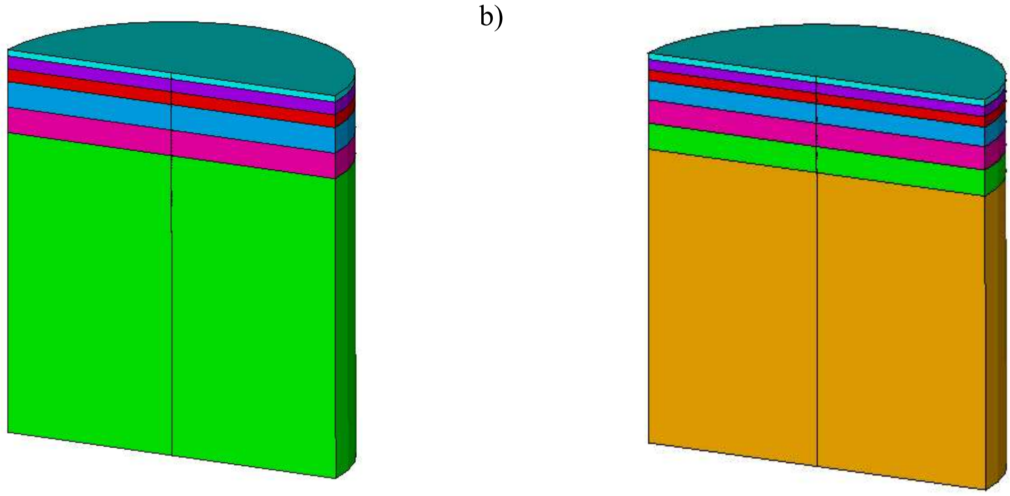

Figure 1 – The pattern of the half model. (a - design No. 1, b - design No. 2)

Рисунок 1 – Візерунок половинної моделі. (а - проект №1, б - проект №2)

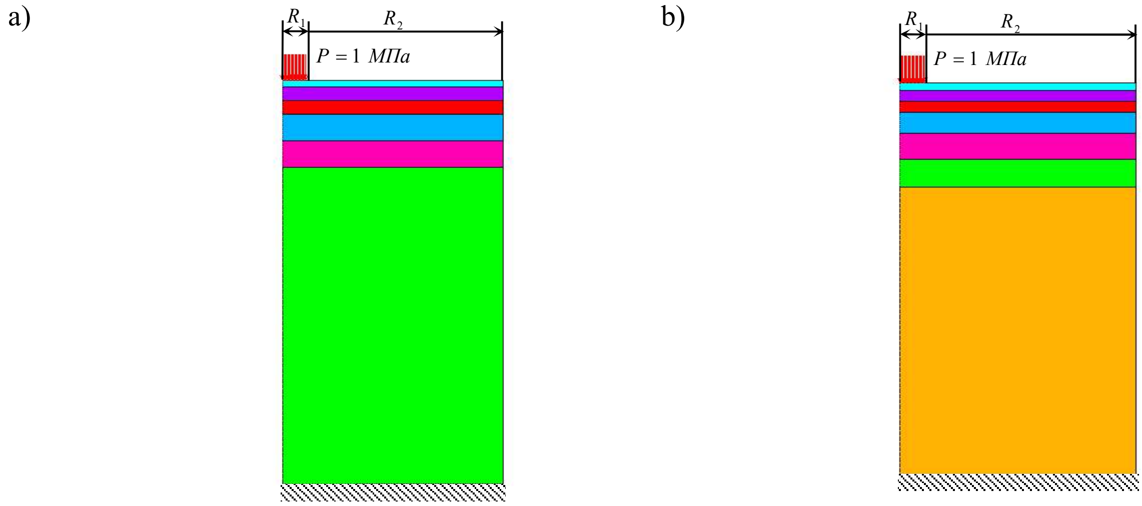

Figure 2 – Cross sections of the rotational bodies corresponding to the models (a - design No. 1, b - design No. 2) with axisymmetric examination
Рисунок 2 – Поперечні перерізи тіл обертання, що відповідають моделям (а - конструкція №1, б - конструкція №2) з осесиметричним дослідженням

The results of maximum displacements under the stamp for the given structures, depending on the temperature and boundary conditions with axisymmetric consideration of the problem, are given in Tables 3, 4.

Table 3 – Maximum displacements under the stamp for design No. 1, depending on the temperature and boundary conditions for axisymmetric consideration of the problem, mm
Таблиця 3 – Максимальні переміщення під штампом для конструкції №1 залежно від температури та граничних умов для осісиметричного розгляду задачі, мм

Variants of boundary conditions	Temperature, ˚C			
	10	40	50	60
1) Complete prohibition of movement on the lateral surface	0,3674	0,8066	0,9369	0,9778
2) Slipping along the side surface permitted	0,511	0,9184	1,044	1,084
3) Moving points of the lateral surface permitted	0,6992	1,103	1,226	1,265

Table 4 – Maximum displacements under the stamp for design No. 2, depending on the temperature and boundary conditions under axisymmetric consideration of the problem, mm
Таблиця 4 – Максимальні переміщення під штампом для конструкції №2 залежно від температури та граничних умов при осісиметричному розгляді задачі, мм

Variants of boundary conditions	Temperature, ˚C			
	10	40	50	60
1) Complete prohibition of movement on the lateral surface	0,3472	0,7017	0,7936	0,8265
2) Slipping along the side surface permitted	0,4938	0,8213	0,9091	0,9409
3) Moving points of the lateral surface allowed	0,6739	1,001	1,087	1,118

Three-dimensional arrangement. Symmetric loading and boundary conditions

The assumption about the symmetry of loading and boundary conditions allows us to consider this task in a three-dimensional arrangement. For this purpose, a prism is isolated from the design, the center of the upper face of which sustains the pressure of 1 MPa, distributed in the middle of the circle with a radius of 16 cm. For the consideration of such a model, we will use the quarter of the model (Fig. 3).

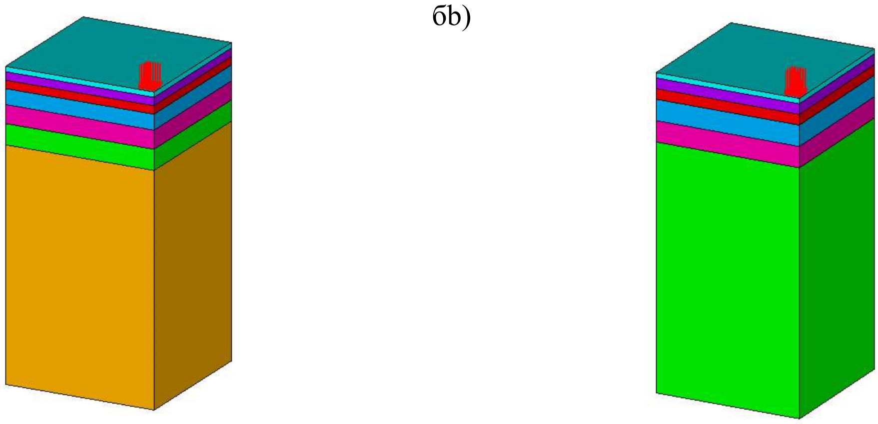

Figure 3 – The scheme of the quarter of the model (a - design No. 1, b - design No. 2)
Рисунок 3 – Схема чверті моделі (а - конструкція №1, б - конструкція №2)

The results of maximum displacements under the stamp for the given structures depending on the temperature and boundary conditions in the three-dimensional consideration of the problem are given in Tables 5, 6.

Table 5 – Maximum displacements under the stamp for design No. 1, depending on the temperature and boundary conditions, mm. Three-dimensional arrangement. Symmetric loading and boundary conditions

Таблиця 5 – Максимальні переміщення під штампом для конструкції №1 залежно від температури та граничних умов, мм. Тривимірна композиція. Симетричне навантаження та граничні умови

Variant of boundary conditions	Temperature, ˚C			
	10	40	50	60
1) Complete prohibition of movement on the lateral surface	0,3798	0,8145	0,9433	0,9831
2) Slipping along the side surface permitted	0,4860	0,8942	1,0190	1,0580
3) Moving points of the lateral surface permitted	0,6427	1,0440	1,1660	1,2050

Table 6 – Maximum displacements under the stamp for design No. 2, depending on the temperature and boundary conditions, mm. Three-dimensional arrangement. Symmetric loading and boundary conditions

Таблиця 6 – Максимальні переміщення під штампом для конструкції №2 залежно від температури та граничних умов, мм. Тривимірна композиція. Симетричне навантаження та граничні умови

Variant of boundary conditions	Temperature, ˚C			
	10	40	50	60
1) Complete prohibition of movement on the lateral surface	0,3589	0,7108	0,8022	0,8342
2) Slipping along the side surface permitted	0,4674	0,7969	0,8848	0,9160
3) Moving points of the lateral surface permitted	0,6184	0,9445	1,0310	1,0610

Three-dimensional arrangement. Unsymmetric loading and boundary conditions

The assumption of asymmetry of loading and boundary conditions allows us to consider this problem in a three-dimensional arrangement. For this purpose a prism is selected from the construction, the face of which sustains the pressure of 1 Mpa, distributed in the middle of a circle with a radius of 16 cm (Fig. 4).

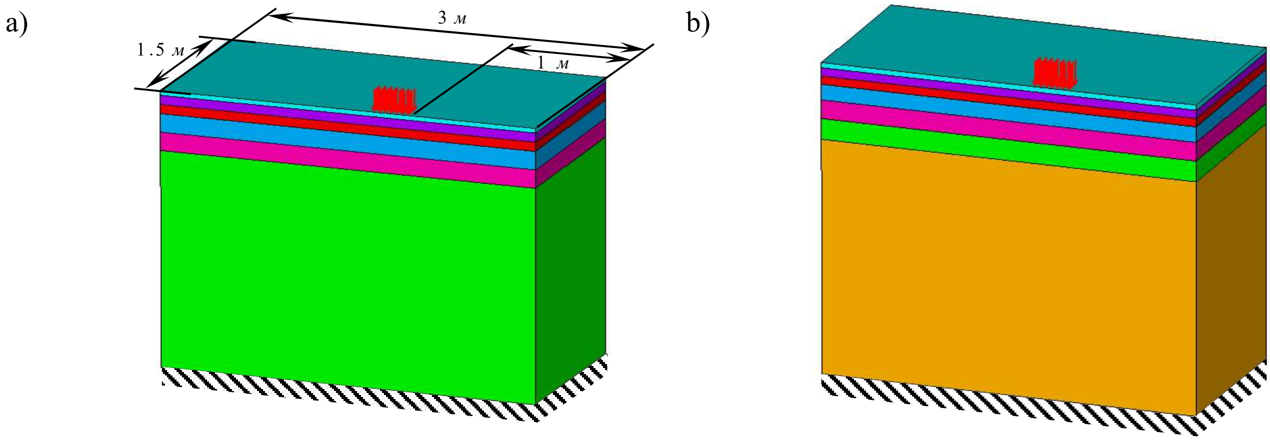

Figure 4 – The scheme of the half model (a - design No. 1, b - design No. 2)
Рисунок 4 – Схема напівмоделі (а - конструкція №1, б - конструкція №2)

For this model we consider the variants of the boundary conditions: the total prohibition of displacements on the lateral surface; slipping along the side surface permitted; slipping along the inner lateral surface and moving of the points of the outer lateral surface permitted; there are no restrictions on the lateral surface. The results of maximum displacements under the stamp for the given structures, depending on the temperature and boundary conditions with non-emermatic load of the problem, are given in Tables 7, 8.

Table 7 – Maximum displacements under the stamp for design No. 1, depending on the temperature and boundary conditions, mm. Three-dimensional arrangement. Unsymmetric loading and boundary conditions
Таблиця 7 – Максимальні переміщення під штампом для конструкції №1 залежно від температури та граничних умов, мм. Тривимірна композиція. Несиметричне навантаження та граничні умови

	Temperature, ˚C			
Variant of boundary conditions	10	40	50	60
1) Complete prohibition of movement on the lateral surface	0,3609	0,7928	0,9214	0,9608
2) Slipping along the side surface permitted	0,4981	0,9012	1,0250	1,0630
3) Slipping along the inner lateral surface and moving the points of the outer lateral surface permitted	0,5480	0,9610	1,0880	1,1270
4) There are no restrictions on the side surface	0,6758	1,0700	1,1920	1,2290

Table 8 – Maximum displacements under the stamp for design No. 2, depending on the temperature and boundary conditions, mm. Three-dimensional arrangement. Unsymmetric loading and boundary conditions
Таблиця 8 – Максимальні переміщення під штампом для конструкції №2 залежно від температури та граничних умов, мм. Тривимірна композиція. Несиметричне навантаження та граничні умови

	Temperature, ˚C			
Variant of boundary conditions	10	40	50	60
1) Complete prohibition of movement on the lateral surface	0,3425	0,6908	0,7822	0,8139
2) Slipping along the side surface permitted	0,4798	0,8058	0,8935	0,9241
3) Slipping along the inner lateral surface and moving the points of the outer lateral surface permitted	0,5264	0,8606	0,9500	0,9810
4) There are no restrictions on the side surface	0,6514	0,9716	1,0570	1,0870

Determination of residual strains of asphalt concrete pavement. A significant disadvantage of the Ukrainian normative documents on the road base design, in particular DCN B.2.3-218-186 [8], is the lack of sections on predicting the condition of road base during its service life. The end of the estimated service life is not associated with the amount of destruction. Put simply, it is not known what the average depth of the rut will be.

Vertical residual strain of compression ε_p is found by the empirical formula (1), obtained in the laboratory during testing of asphalt concretes, depending on the temperature *T* and the number of previous loads *N*. In this test repeated loads were carried out without side limitation, and then, the coefficients were updated according to the field data [9]:

$$h_{a/б}(t,T(t)) = \frac{\varepsilon_p}{\varepsilon_r} = \beta_{r1} \cdot a_1 \cdot T \cdot a_2 \cdot \beta_{r2} \cdot N \cdot a_2 \cdot \beta_{r3} \quad (1)$$

where ε_p - accumulated residual vertical strain from *N* loaded at temperature *T (F)*;

ε_r - is the vertical strain at this point, calculated from the theory of elasticity and dependent on the parameters of the axes of the layer system.

As a result of the laboratory study of repeated loads of asphalt concrete, we obtain the following expression (2):

$$\frac{\varepsilon_p}{\varepsilon_r} = 10^{-3,1555} \cdot \left(\frac{9}{5} \cdot Tc + 32\right)^{1,734} \cdot N^{0.3994} \quad (2)$$

The correct setting of boundary conditions for models of such designs is a complicated task. The deformation of a model with a boundary-free lateral surface can be the upper limit of the deformations of the real structure, and the lower limit is the deformation of the model with a rigidly restrained lateral surface. As the calculations have shown, the difference between them in some cases can reach 50%, so the deformation of the model with an "intermediate state" of the boundary conditions is taken for the evaluation of structural deformation.

Under axisymmetrical arrangement it was possible to achieve numerical convergence of strains with grids condensed up to 16080 elements, while reaching numerical convergence with a relative error of 1% in the three-dimensional arrangement required 1006000 elements, and further condensation of the grid encountered significant difficulties in the calculation.

The analysis of the results has shown that for the elastic strains estimation axisymmetrical arrangement is enough, whereas in the calculation of strength it is necessary to use the three-dimensional arrangement and the boundary conditions as close to the real ones as possible, since the boundary conditions and the position of the load essentially affect the redistribution of the tensile stresses zones, and not so much the size of strains.

On the basis of the obtained results, it can be concluded that the maximum displacements, and hence the rutting of the asphalt concrete pavement of non-rigid road base, occurs in design No. 1, in which reinforced layers were not applied. The results of the study indicate that the rutting in asphalt concrete layers in the structure with reinforced materials is up to 56% less than in the analogous but without the use of reinforced materials. Depending on the conditions of the boundary state, the rutting of pavement design increases to 28%.

References

1. DBN V.2.3-4: 2015. Highways. Part I. Design. Part II. Construction. (Ukr)

2. Technical rules for repair and maintenance of public roads of Ukraine: P-G. 1-218-113: 2009 / K. – Official publ. – K .: Ukravtodor, 2010. – 168 p. – (Ukravtodor Regulations). (Rus)

3. Ivanov I. N. Design and calculation of non-rigid road bases / N. N. Ivanov, A. M. Kriviskii, M. B. Korsunskii. – M.: Transport, 1973. – 328 p. (Rus)

4. Korsunskii M. B., Bulavko A. G. Stresses and strains of multilayer elastic-isotropic systems with an axisymmetric load. In the book: Practical methods for determining the stress-strain state of road structures. M., "Transport" 1966, pp. 5–124. (Proceedings Soyuzdor- Research Institute, Vol. 6). (Rus)

5. Yakovlev Y. M., Konovalov C. B., Leyvak V. A. Shagal L.V. The study design parameters to assess the strength and the calculation of the gain non-rigid pavements in the test of the dynamic load. Rostov-on-Don: Vol. Rostov Regional board of NTR, 1977. – 31. (Rus)

6. Brodskii B. Z. Regression analysis when planning the composite second order of a special type // Scientific Council for the Complex Problem "Cybernetics", information materials. – M.: Academy of Sciences of the USSR – 1970. – 145 p. (Rus)

7. Fedorov B.V. The theory of optimal experiment. – Moscow: Science. – 1971. – 214 p. (Rus)8. DBN V.2.3-218-186-2004. Road base of non-rigid type. Institutional building codes of Ukraine. Kyiv: State Road Service of Ukraine "Ukravtodor", 2004. – 71 p. (Ukr)9. AASHTO. – Mechanistic-Empirical Pavement Design Guide. A Manual of Practice. Interim Ed. 2008.

МЕТОД ОЦІНКИ СТІЙКОСТІ ПОКРИТТЯ НЕЖОРСТКОГО ДОРОЖНЬОГО ОДЯГУ ДО УТВОРЕННЯ КОЛІЇ ЗА РАХУНОК МЕТОДУ СКІНЧЕННИХ ЕЛЕМЕНТІВ

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Анотація. В статті наведена розрахунок напружено-деформованого стану асфальтобетонного покриття методом скінченних елементів із застосуванням програмного комплексу Ansys.

Недостатня стійкість асфальтобетонного покриття автомобільних доріг і вулиць до колійності з утворенням зсувів, напливів, колій суттєво знижує як міцність всієї конструкції дорожнього одягу, так і особливо рівень безпеки руху за рахунок створення ефекту аквапланування в місцях застою води та зимової слизькості.

Результати проведених розрахунків дають можливість теоретично визначити колію асфальтобетонного покриття в залежності від заданої кількості проходів автомобіля та температури асфальтобетонного покриття.

Ключові слова: напружено-деформований стан, колієстійкість, асфальтобетонне покриття, залишкові деформації