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IMPACT OF DEFECTS AND DESTRUCTION ON THE CHANGE IN THE BEARING CAPACITY AND DURABILITY OF RIGID PAVEMENT STRUCTURES

Part 1. Clarification of the stress-strain state of a cement concrete slab

ВПЛИВ ДЕФЕКТІВ ТА РУЙНУВАНЬ НА ЗМІНУ НЕСНОЇ ЗДАТНОСТІ ТА ДОВГОВІЧНОСТІ ЖОРСТКИХ ПОКРИТТІВ ДОРОЖНІХ КОНСТРУКЦІЙ

Частина 1. Уточнення напружено – деформованого стану цементобетонної плити

Igor Gameliak, *Sc.D., Professor, National Transport University, Head of department «*
transport infrastructure objects and geodesy», e-mail: gip65@gmail.com, +3805035
01010, Kyiv, Omelyanovich Pavlenko str. 1, of. 346

https://orcid.org/0000-0001-9246-7561

Anna Kharchenko, *Sc.D., Professor, National Transport University, Professor of Transport Construction and Property Management Department, e-mail: anna-x3@ukr.net, tel. +380442807909, Ukraine, 01010, Kyiv, Omelyanovich Pavlenko str. 1, of. 323*

https://orcid.org/0000-0001-8166-6389

Andij Dmytrychenko, *Candidate of Engineering Sciences, Associate Professor, National Transport University, Associate Professor of Department Transport Law and Logistic, e-mail: andrew_d@ukr.net, +380502816006, Ukraine, 01010, Kyiv, Omelyanovich Pavlenko str. 1*

https://orcid.org/0000-0001-6144-7533

Summary. Various theoretical models and formulas are considered, in particular the Winkler-Zimmermann hypothesis and the Westergaard method, for calculating the stresses and deflections of slabs under loading in the center, at the edge and at the corner. The main type of failure of rigid road pavements is the chipping of the corners of the slabs, which is often observed in concrete without reinforcement. The analysis shows that the most dangerous location of the load is at the corner of the slab, where the stresses are 1.8 times greater than in the center.

Keywords: rigid road pavement, defects and destruction, cracks, transition coefficient, slab, deflection, bending moment

Introduction.

Under the influence of vehicles and weather and climatic factors, micro defects accumulate in the layers of materials treated with binders, which eventually develop into macro cracks; contact destruction of crushed stone grains occurs with the appearance and accumulation of small particles surrounding these grains and in the presence of water, small parts of the destruction are plasticized; the material of the drainage layer is silted, which impairs its filtration capacity and, in combination with increased cracks in the connective layers and the flow of atmospheric water, this leads to waterlogging of the soil. All this, ultimately, leads to a decrease in the overall modulus of elasticity of the road pavement.

For the first time, an attempt to assess the change in layer moduli depending on the condition of the pavement in terms of destruction was made at the KhADI by prof. A.K. Birulya [1]. When implementing VSN 46-72 by the authors of the work [2], on the basis of experimental data from the Khadi, it was recommended to multiply the calculated values of the layer modulus by decreasing coefficients, the values of which depend on the presence of defects and destruction, depending on the degree of their development, after a visual assessment of the condition of the layers when opening the pavement. These results, practically unchanged, are now accepted in the pavement management system (SUSP), which is implemented by NTU specialists in the organizations of the corporation "Ukravtodor".

The paper [3] presents the results of measuring elastic deflections with an increase in the number of axial loads applied during the testing of road pavement. In this case, by the time visible cracks appeared on the surface of the pavement, the deflection increased by 1,8 times, and after their development - by 2,3 times compared to the deflection at the beginning of the tests.

Presenting main material.

During the inspection of roads, similar results were obtained, which show that in the destroyed areas the average modulus of elasticity is 1,9 times less than the average total modulus of elasticity of the road pavement in undeformed areas [3-4].

In Belgium [4], the results of experimental surveys proposed the following dependence for calculating the equivalence coefficient of cement concrete with defects relative to crushed stone:

$$a_l = \left(E_l / E_{sch}\right)^{1/3}, \tag{1}$$

where E_l is the modulus of elasticity of cement concrete;

E_{sch} = 500 MPa – modulus of elasticity of the crushed stone layer – are made dependent on the condition of the cement concrete pavement.

So, for a new pavement a_l = 2.7, and for a very badly destroyed a_l = 1.0, which corresponds to crushed stone. Then the decreasing coefficients to the modulus of elasticity of cement concrete have the following values (Table 1):

In general, it can be stated that despite the significant impact of deformations and destruction on the strength of the road pavement, the results of direct measurement of the reduction in the bearing capacity of the pavement structure are clearly not enough. There are even fewer works devoted to the theoretical description of the impact of defects and destruction on changes in the strength of the pavement structure during operation.

The purpose of the work is to establish mathematical dependencies to assess the effect of mechanical damage to the pavement on the overall modulus of elasticity of the pavement.

Research review. Cement concrete pavements are designed with the assumption that the slab rests on a perfectly flat base, not taking into account the joint work between the concrete and the substrate.

In the United States, several methods of designing cement-concrete pavements have been developed [5 - 10].

***Table 1** – Reduction coefficients to the modulus of elasticity of cement concrete*
***Таблиця 1** – Коефіцієнти зниження модуля пружності цементобетону*

New pavement	1,00
No cracks, moderate deformities	0,80
Crack insulation, moderate deformations	0,41
Frequent cracks, crack mesh, individual deformities	0,17
Frequent cracks, a network of cracks or traces of repair on a large part of the coastline, severe or frequent deformations	0,05

The main ones are:
- ACPA (American Cement Concrete Pavement Association) method since 1991,
- AASHTO method (American Association of State Road and Transportation Employees) from 1993 [5, 6].

The above methods, which are successfully used in the USA, are based on the theoretical solution of Westergaard [7 - 8], modified by local conditions, according to which, taking into account the coefficient of the bedding Ks of the substrate and the tensile strength when bending cement concrete, the thickness of the concrete slab is established.

In our country, the calculation of rigid garments is carried out in accordance with SNiP 2.05.08-85 for aerodrome pavements [9] and **GBN** V.2.3-37641918-557 for road pavements [10].

The experience of inspecting linear infrastructure facilities indicates that the first and main type of destruction is breaking off the corners of pavements. Therefore, it is important to find theoretical confirmation of this mechanism.

This problem is important for new types of rolled concrete pavements, where, for technological reasons, there are no rebar and reinforcement in the seam area.

The purpose of the study: to establish analytical dependencies for calculating the impact of cracks and joints on reducing the bearing capacity and durability of cement concrete pavements.

Problem statement. The mechanism of destruction of plates in time can be divided into the following stages: exceeding the permissible loads on the support, wheel or axle and breaking the corner of one plate → water flowing into cracks and seams and soaking the plate at a cracked corner and weakening the base → sedimentation of the broken part → breaking the corner of the plate located in front or in another lane of movement → the settlement of parts, broken off with stagnant water and filling with dirt → subsequent breaking off of the body of the plate with the formation of block cracks → grinding of block cracks with the formation of a network of cracks "crocodile skin" → complete loss of bearing capacity (Table 2).

This situation is typical for objects that have served more than 40 ... 50 years at rated load and for newly built, after 3-4 years with a significant excess of permissible design loads.

The coefficient of bringing to the equivalent bearing capacity for fractures in the form of breaking the corner of the slabs is located (in the absence of reinforcement of the slabs or the presence of rebars in the joints, etc.) as the stress ratio at the corner of the slab σ_c to the center of the slab σ_i:

$$K_{c\_i} = \frac{\sigma_c}{\sigma_i}. \quad (2)$$

The coefficient of bringing to the equivalent bearing capacity for fractures in the form of breaking the edge of the slabs is located (in the absence of reinforcement of the slabs or the presence of pins in the joints, etc.), as the ratio of stress at the edge σ_{eg} of the slab to the center of the slab σ_i:

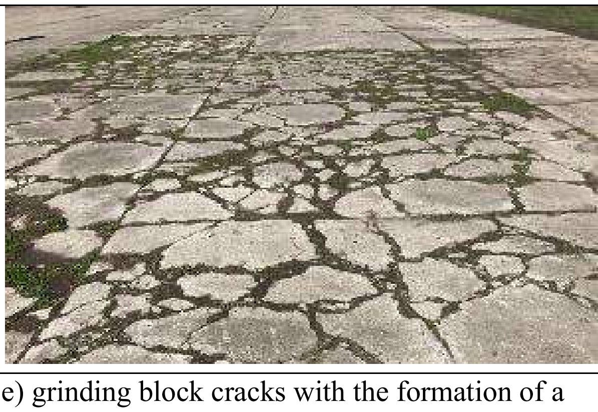
$$K_{eg\_i} = \frac{\sigma_{eg}}{\sigma_i}. \quad (3)$$

Reduction coefficient, as the ratio of stress at the corner of the slab to the edge of the slab:

$$K_{c\_eg} = \frac{\sigma_c}{\sigma_{eg}}. \quad (4)$$

***Table 2** – Mechanism (dynamics in time) of destruction of cement-concrete slabs of linear infrastructure facilities (roads, airfields, container sites of ports, logistics centers, etc.)*

***Таблиця 2** – Механізм (динаміка в часі) руйнування цементобетонних плит лінійних інфраструктурних об'єктів (доріг, аеродромів, контейнерних майданчиків портів, логістичних центрів тощо)*

Destruction of cement-concrete slabs	Destruction of cement-concrete slabs in time
	
a) breaking off the corner of the slab	b) subsidence and breaking off of two or three adjacent corners of the slabs
	
b) the development of a branch of cracks from corner cracks with the division of the plates into three or four parts	c) further subsidence and breaking off of four adjacent corners of the slabs with formation of cracks parallel and perpendicular to the corner ones
	
d) progressive destruction of slabs with the formation of block cracks (stagnation of water in subsidence zones, waterlogging of the base)	e) grinding block cracks with the formation of a network of cracks "crocodile skin".

Similarly, for the second group of boundary states, we have the corresponding ratios of deflection the corner δ_c and egle δ_{eg} to deflections center of the slab δ_i:

$$\Delta_{c\_i} = \frac{\delta_c}{\delta_i}, \qquad \Delta_{eg\_i} = \frac{\delta_{eg}}{\delta_i}, \qquad , \Delta_{c\_eg} = \frac{\delta_c}{\delta_{eg}}. \tag{5}$$

Assumptions of the Westergaard method

The formulas for determining the thickness of a concrete slab were determined using the Winkler-Zimmermann hypothesis, which assumes that the response of the soil to external loads is directly proportional to the magnitude of the load [6 - 7]:

Three cases of load installation are considered: in the center of the slab, at the edge and in the corner of the slab,

With the external load, the safety factor of 1,15 and the dynamic impact of the load due to the coefficient of dynamism K_{dyn} = 1,2 … 1,3 should be taken into account.

Theoretical calculation model

In the computational model of the method, a slab resting on a Winkler base is characterized by a coefficient of base (soil) resistance (bedding) *K*. The material of the slab is characterized by the following parameters: modulus of elasticity of cement concrete *E* and Poisson's coefficient ν. 1 below.

The calculation of the stress according to the tensile criterion during bending of monolithic layers is performed depending on the contact conditions between the layers:

a) "soldered" contact, when the layers are completely interlocked;

b) contact with "slippage" – incomplete contact, taking into account the shear;

c) "smooth or slippery contact" - there is no grip.

The first case is practically difficult to implement. The second most closely matches the contact conditions for the pavement layers. The most dangerous for the work of the pavement is the last case.

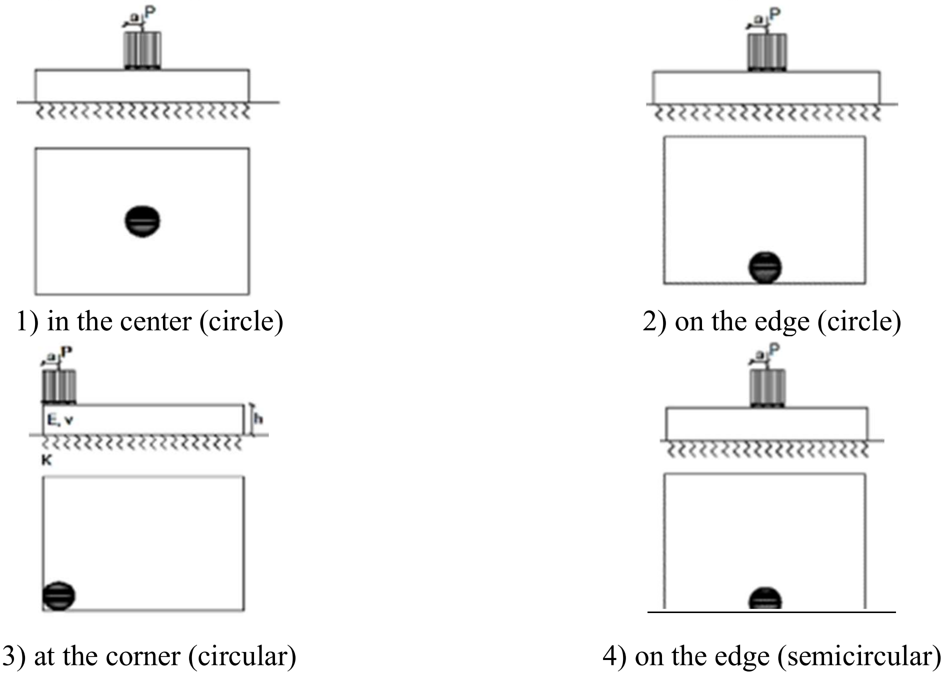


***Figure 1** – Model for calculating pavement by the Westergaard method [6 - 7]*

***Рисунок 1** – Модель для розрахунку покриття методом Вестергаарда [6-7]*

According to the assumptions, the methods of stress in the plate are determined in three places, using the following ratios [6 - 23]:

I. INTERIOR LOADING (LOAD IN THE PLATE'S CENTER)

As defined by Westergaard, this is the case of a wheel load at a "considerable distance from the edges," [14] with pressure "assumed to be uniformly distributed over the area of a small circle with radius a" [15]. After an extensive literature survey and comparisons with finite element results, the following interior loading equations are considered to be in their most general form.

Maximum bending stress, σ_{ri}:

1.Ordinary theory of Westergaard's

$$\sigma_{i\_orig} = \frac{3P}{h^2} \cdot \frac{(1+\mu)}{2\pi} \cdot \left(\log\left(\frac{1}{a}\right) + 0,5 - \gamma \right) + \frac{3P}{64h^2}(1+\mu)\left[\left(\frac{a}{1}\right)^2\right]. \quad (6)$$

2. Special theory:

$$\sigma_{i\_spec} = \frac{3P}{h^2} \cdot \frac{(1+\mu)}{2\pi} \cdot \left(\log\left(\frac{2 \cdot l}{b}\right) + 0,5 - \gamma \right) + \frac{3P}{64h^2}(1+\mu)\left[\left(\frac{b}{1}\right)^2\right]. \quad (7)$$

3. For square:

$$\sigma_{i\_sque} = \frac{3P}{h^2} \cdot \frac{(1+\mu)}{2\pi} \cdot \left(\log\left(\frac{2 \cdot l}{cl}\right) + 0,5 - \gamma \right) + \frac{3P}{64h^2}(1+\mu)\left[\left(\frac{c^1}{1}\right)^2\right]. \quad (8)$$

4. For the center of the slab from the circular load:

At large values of the pavement thickness, which is typical for aerodromes and roads of I - II category with cement-concrete pavement, the solution of the Westergaard theory of thick plates can be used to calculate the maximum tensile stresses on the lower surface of the plate:

$$(\sigma_r)_{\max} = 0,275 \cdot (1+\mu)\frac{P}{h_r{}^2}(4\lg\left(\frac{E \cdot h^3}{12(1-\mu^2)K \cdot b^4}\right) + 1,069), \quad (9)$$

5. Maximum deflection, for load distributed in a circle, δ_i:

$$\delta_{i\_orig} = \left(\frac{P}{8kl^2}\right) \cdot \left[1 + \left(\frac{1}{2\pi}\right)\left(\ln\left(\frac{a}{2l}\right) + \gamma - \frac{5}{4}\right) \cdot \left(\frac{a}{l}\right)^2\right] \quad (10)$$

II. EDGE LOADING

Westergaard defined edge loading as the case in which "the wheel load is at the edge, but at a considerable distance from any corner." The pressure is assumed to be "distributed uniformly over the area of a small semi-circle with the center at the edge" (~). Equations for a circular load at the edge were first presented in 1948 [16]. The most general forms of the edge loading formulas follow.

Equations for circular load at edges were first introduced in 1948 [16]. The most common forms of formulas for plate edge loads are given below:

Maximum bending stress, σ_{eg}.

1. Conventional theory (semicircle):

$$\sigma_{e\_WOT} = \frac{0,529P}{h^2} \cdot (1 + 0,54\mu) \cdot \left(\log\left(\frac{E \cdot h^3}{ka_2{}^4}\right) - 0,71 \right), \quad (11)$$

2. Special theory (semicircle):

$$\sigma_{e\_WST} = \frac{0,529P}{h^2} \cdot (1+0,54\mu) \cdot \left(\log\left(\frac{E \cdot h^3}{kb_2^{\ 4}} \right) - 0,71 \right), \tag{12}$$

3. "New" formula (circle):

$$\sigma_{e\_EIC} = \left[\frac{3P}{\pi h^2} \cdot \left[\frac{(1+\mu)}{(3+\mu)} \right] \right] \cdot \left[\ln\left(\frac{Eh^3}{100ka^4} \right) + 1,84 - \frac{4\mu}{3} + \left(\frac{1-\mu}{2} \right) + 1,18(1+2\mu)\left(\frac{a}{l} \right) \right], \tag{13}$$

4. "New" formula (semicircle):

$$\sigma_{e\_EIC} = \left[\frac{3P}{\pi h^2} \cdot \left[\frac{(1+\mu)}{(3+\mu)} \right] \right] \cdot \left[\ln\left(\frac{Eh^3}{100ka_2^{\ 4}} \right) + 3,84 - \frac{4\mu}{3} + \left(\frac{1+2\mu}{2} \right) \right] \cdot \frac{a_2}{l}, \tag{14}$$

5. Simplified "New" formula (semicircle):

$$\sigma_{e\_SEIS} = \left[\left(\frac{-6P}{h^2} \right) \cdot (1+0,5\mu) \cdot \left[0,489\log\left(\frac{a_2}{1} \right) + 0,091 - 0,027\left(\frac{a_2}{l} \right) \right] \right], \tag{15}$$

6. Simplified "New" formula (circle) (Loseberg equation):

$$\sigma_{e\_SEIC} = \left(\frac{-6P}{h^2} \right) \cdot (1+0,5\mu) \cdot \left[0,489\log\left(\frac{a}{1} \right) + 0,012 - 0,063\left(\frac{a}{l} \right) \right], \tag{16}$$

7, The Kelly equation for edge load is represented below with b, which is equal to the load radius of the plate [17]:

$$\sigma_{\max} = 0,529(1+0,54\mu)\frac{P}{h^2}\log\left(\frac{0,20Eh^3}{Kb^4} \right), \tag{17}$$

Maximum deflection, δ_{eg}:

1. Original formula:

$$\delta_{e\_загальне} = (1+0,4\mu)\left(\frac{1}{\sqrt{6}} \right) \cdot \left(\frac{P}{kl^2} \right), \tag{18}$$

2. "New" formula (circle):

$$\delta_{e\_EIC} = \left[\frac{P(2+1,2\mu)^{\frac{1}{2}}}{(Eh^3k)^{\frac{1}{2}}} \right] \cdot \left[1 - (0,76+0,4\mu)\left(\frac{a}{l} \right) \right], \tag{19}$$

3. New formula (semicircle):

$$\delta_{e\_EIS} = \left[\frac{P(2+1,2\mu)^{\frac{1}{2}}}{(Eh^3k)^{\frac{1}{2}}} \right] \cdot \left[1 - (0,323+0,17\mu)\left(\frac{a_2}{l} \right) \right], \tag{20}$$

4. Simplified "new" formula (semicircle):

$$\delta_{e\_ELS} = \left(\frac{1}{\sqrt{6}} \right) \cdot (1+0,4\mu)\left(\frac{P}{kl^2} \right)\left[1 - 0,323(1+0,5\mu)\left(\frac{a_2}{l} \right) \right], \tag{21}$$

5. Simplified "new" formula (circle):

$$\delta_{e\_ELC} = \left(\frac{1}{\sqrt{6}}\right)\cdot(1+0,4\mu)\left(\frac{P}{kl^2}\right)\left[1-0,760(1+0,5\mu)\left(\frac{a}{l}\right)\right], \tag{22}$$

III. CORNER LOADING

Of the three fundamental cases of loading investigated by Westergaard, corner loading is undoubtedly the most obscure and debatable. The theoretical background for maximum corner deflection and stress equations is particularly weak. Their semiempirical and approximate nature has led to numerous revisions and modifications in the years since their original publication, in an attempt to reconcile observed slab behavior with theory. These are discussed by Kelley [17] and Pickett [18] and are summarized as follows:

Maximum bending stress, σ_{cor}:

1. Goldbeck [19], Older [20]:

$$\sigma_{cl} = \left(\frac{3P}{h^2}\right), \tag{23}$$

2. Westergaard [5] Ioannides et al.:

$$\sigma_{c2} = \left(\frac{3P}{h^2}\right)\left[1,0-\left(\frac{a_1}{l}\right)^{0,6}\right], \tag{24}$$

or

$$\sigma_{\max} = \frac{3P}{h^2}\left(1-\left(\frac{1-41b}{\left(\frac{Eh^3}{12(1-\mu^2)K}\right)^{0,25}}\right)^{0,6}\right), \tag{25}$$

3. Bradbury [21]:

$$\sigma_{c2a'} = \left(\frac{3P}{h^2}\right)\left[1,0-\left(\frac{a}{l}\right)^{0,6}\right], \tag{26}$$

4. Kelly [17], Teller and Sutherland [22]:

$$\sigma_{c3} = \left(\frac{3P}{h^2}\right)\left[1,0-\left(\frac{a_1}{l}\right)^{1,2}\right]. \tag{27}$$

5. Spangler [16]:

$$\sigma_{c4} = \left(\frac{3,2\cdot P}{h^2}\right)\left[1,0-\left(\frac{a_1}{l}\right)\right]. \tag{28}$$

6. Pickett [18]:

$$\sigma_{c5}(Pa) = \frac{4,2P}{b^2}\left(1-\left(\frac{\sqrt{a/\ell}}{0,925+0,22(a/\ell)}\right)\right). \tag{29}$$

7. Geoffroy:

$$\sigma_{k\_Gam} = \frac{P}{h^2}\left[2,7202e^{1,741\cdot\left(\frac{a}{l}\right)}\right]. \tag{30}$$

Geoffroy and Pickett's formulas differ only by a factor of (1+μ).

8. Finite element solution [23]:

$$\sigma_c = \left(\frac{3P}{h^2}\right)\left[1,0-\left(\frac{c}{l}\right)^{0,72}\right]. \tag{31}$$

9. Suggested based on research data:

$$\sigma_{c\_Gam} = (1+\mu)\cdot\frac{P}{h^2}\left[e^{1-(e-1)\cdot\left(\frac{a}{l}\right)}\right]. \tag{32}$$

Maximum deflection, $\delta_{cor.}$:

11. Original formula Westergaard:

12.

$$\delta_c = \left(\frac{P}{kl^2}\right)\left[1,1-0,88\left(\frac{a_1}{l}\right)\right]. \tag{33}$$

11.Approximation of calculations by the finite element method:

$$\delta_{cMCE} = \left(\frac{P}{kl^2}\right)\left[1,205-0,69\left(\frac{c}{l}\right)\right]. \tag{34}$$

The above formulas indicate:

P – the value of the applied load on the wheel;

h – the required thickness of the cement concrete slab;

Plate length, not less than $L = 5\cdot l$;

l – the radius of relative rigidity, determined by the dependence [10 -13]:

$$l = \sqrt[4]{\frac{E\cdot h^3}{12\cdot\left(1-\nu^2\right)\cdot K_{os}}}, \tag{35}$$

where Z=0,2; for reliability 80%.

A – the radius of the loading surface;

ν – the Poisson's ratio for cement concrete;

$a_1 = a\cdot\sqrt{2}$; $b = \sqrt{1,6\cdot a^2+h^2}-0,675\cdot h$ - equivalent radius of stress distribution on the bottom surface of the plate,

E – the modulus of elasticity of the cement concrete from which the slab is made;

K_{os} – the coefficient of base (soil) resistance under the cement concrete slab (cement concrete on the existing base and soil):

$$b_k = \sqrt{1,6\cdot\frac{D^2}{4}+h_r^2}-0.675\cdot h_r, \text{ for } D/2 < 1,724\cdot h, \quad b_k = \frac{D}{2} \text{ for } D/2 \geq 1,724\cdot h, \tag{36}$$

The latter formula is widely used to calculate aerodrome cement concrete pavements.

The change in tensile stresses during bending for the center, edge (according to the refined Westergaard formulas) and corner of the plate when calculated according to our approximations depending on the thickness of the plate is shown in Fig. 2.

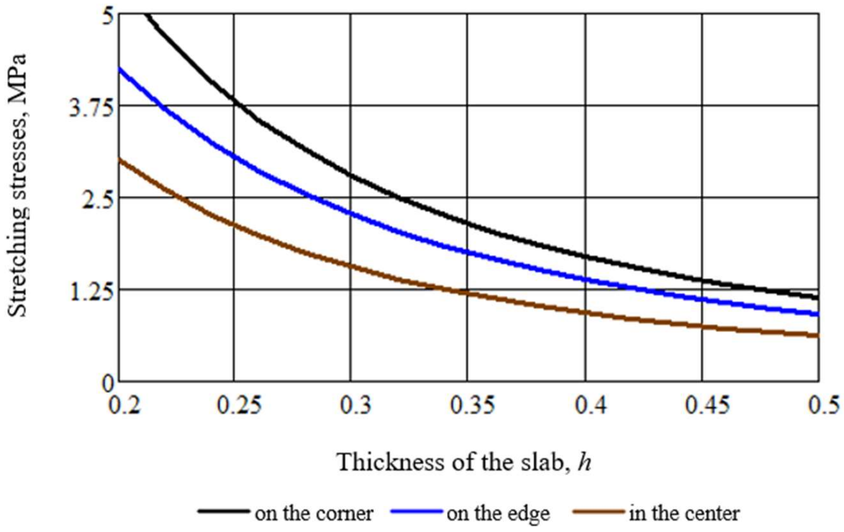


Figure 2 *– Comparison of tensile stresses during bending for the center, edge (according to the refined Westergaard formulas) and corner of the plate when calculated according to our approximations*

Рисунок 2 *– Порівняння напружень розтягу під час згинання для центру, краю (згідно з уточненими формулами Вестергаарда) та кута пластини при розрахунку за нашими наближеннями*

Conclusions

The paper presents an analysis of the analytical relationships for determining stresses and strains in a cement concrete slab, used in various codes for the design of rigid pavements.

The comparison is made starting with the pioneering analytical work of N.M. Westergaard, which has been the basis of slab pavement design since the 1920s. Every code of practice published since then contains a reference to the “Westergaard solution”.

These solutions are obtained for three specific loading conditions (internal, edge and corner) and assume a slab of infinite or semi-infinite dimensions. Since their first appearance, starting in the early 1920s, the Westergaard equations have often been misquoted or incorrectly applied in subsequent publications.

Westergaard’s original equation for the edge stress is incorrect. Instead, the long-ignored equation given in his 1948 paper should be used. Improved expressions for maximum angular loads have been developed. Dependencies for calculating deflections in a cement concrete slab of a rigid road pavement have also been analyzed.

The specified dependencies are recommended for use in the development of domestic regulatory documents for the design of rigid road pavements.

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ВПЛИВ ДЕФЕКТІВ ТА РУЙНУВАНЬ НА ЗМІНУ НЕСНОЇ ЗДАТНОСТІ ТА ДОВГОВІЧНОСТІ ЖОРСТКИХ ПОКРИТТІВ ДОРОЖНІХ КОНСТРУКЦІЙ

Частина 1. Уточнення напружено – деформованого стану цементобетонної плити

Гамеляк Ігор Павлович, доктор технічних наук, професор, Національний транспортний університет, завідувач кафедри системного проєктування об’єктів транспортної інфраструктури та геодезії , e-mail: gip65n@gmail.com., +380503524124, https://orcid.org/0000-0001-9246-7561

Харченко Анна Миколаївна, доктор технічних наук, професор, Національний транспортний університет, професор кафедри транспортного будівництва та управління майном, e-mail: anna-x3@ukr.net, тел. +380442807909, Україна, 01010, м. Київ, вул. Омеляновича-Павленка, 1, к. 323, https://orcid.org/0000-0001-8166-6389

Дмитриченко Андрій Миколайович, кандидат технічних наук, Національний транспортний університет, доцент кафедри транспортного права та логістики, e-mail: andrew_d@ukr.net, +380502816006, https://orcid.org/0000-0001-6144-7533

Анотація: Стаття присвячена оцінці впливу механічних пошкоджень покриття цементобетонних жосрткх дорожніх одягів на їх загальний модуль пружності та довговічність. Зазначається, що руйнування, спричинені транспортними засобами та погодними умовами, знижують модуль пружності дорожнього покриття.

Розглянуто різні теоретичні моделі та формули, зокрема гіпотезу Вінклера-Циммермана та метод Вестергаарда, для розрахунку напружень та прогинів плит під навантаженням у центрі, на краю та на куті. Основним типом руйнування жорстких дорожніх покриттів є відколювання кутів плит, яке часто спостерігається в бетоні без армування. Аналіз показує, що найбільш небезпечним є розташування навантаження на куті плити, де напруження в 1,8 раз більші ніж по центру.

Ключові слова: жорстке дорожнє покриття, дефекти та руйнування, тріщини, коефіцієнт переходу, плита, прогин, згинальний момент.

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