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

Part 2. Assessment of the change in the coefficient of reduction of bearing capacity and deformability of road and airfield pavement

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

Частина 2. Оцінка зміни коефіцієнта зниження несної здатності та деформативності дорожнього та аеродромного покриття

Igor Gameliak, *Sc.D., Professor, National Transport University, Head of department «System design of transport infrastructure objects and geodesy», e-mail: gip65@gmail.com, +380503524124, Ukraine, 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. The article is devoted to the assessment of the influence of mechanical damage to cement concrete pavements on their overall modulus of elasticity and durability. It is noted that the destruction caused by vehicles and weather conditions reduces the modulus of elasticity of the road pavements. The studies described in the article show that on damaged road sections the average modulus of elasticity can be 1.9 times lower than on undamaged ones.

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 presence of a through crack can increase the deflection of the slab by 1.3-2.7 times.

The authors concluded that it is more logical to consider the destruction due to a decrease in the modulus of elasticity of cement concrete, rather than due to a decrease in the layer thickness. The article also analyzes the influence of the modulus of elasticity of the base on the deflection of the slab. The optimal value for highways is 120-150 MPa. A formula is proposed for calculating the coefficients of reduction to equivalent bearing capacity for destruction in the form of chipping of corners and edges of slabs.

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

Presentation of the main material

The limiting bending moment m_u per unit cross-sectional width for concrete and reinforced concrete covers is determined by the formula [1]:

$$m_u = \frac{\gamma_c \cdot R_{btb} \cdot h^2 \cdot k_u}{6}, \tag{1}$$

where, γ_c – the coefficient of working conditions;

R_{btb} – the estimated value of tensile strength during concrete bending,

k_u – the fatigue coefficient:

$$k_u = 2 - 0{,}167 \cdot \lg{(U_d)}, \tag{2}$$

here U_d is the given number of applications of the design axes of loads.

For rigid road pavements, the fatigue coefficient of concrete under repeated loading is determined by the formula:

$$k_y = 1{,}08 \cdot N_{pt}^{0{,}063}, \tag{3}$$

where N_{pt} - calculated total repetition of design loads for a service life of t years.

Ultimate (design) tensile strength of concrete in bending fatigue $R_{btb}(N_{pt})$ from the number of load cycles Npt is determined by the formula (A.1) [2]:

- for road pavements:

$$R_i^p = B_{btb} \cdot K_F \cdot 1{,}08 \cdot N_{pt}^{0{,}063} \cdot {'}K_m, \tag{4}$$

where K_F – coefficient that takes into account the reduction in strength due to repeated freeze-thaw cycles, $K_F = 0{,}95$;

K_m – strength gain coefficient: for natural hardening concrete at air temperatures above 10 ºC $K_m = 1.2$; for natural hardening concrete at air temperatures below 10 ºC and during winter concreting $K_m = 1$.

- for airfield pavements [1]:

$$R_{btb}(N_{pt}) = \gamma_c \cdot R_{btb} \cdot (2 - 0{,}167 \lg(N_{pt}), \tag{5}$$

Despite the fact that different logarithmic (2) and power (3) dependences are used to calculate the limit condition (Fig. 1), taking into account the number of cycles to failure, almost the same value of the ultimate strength is obtained, taking into account fatigue (Fig. 2).

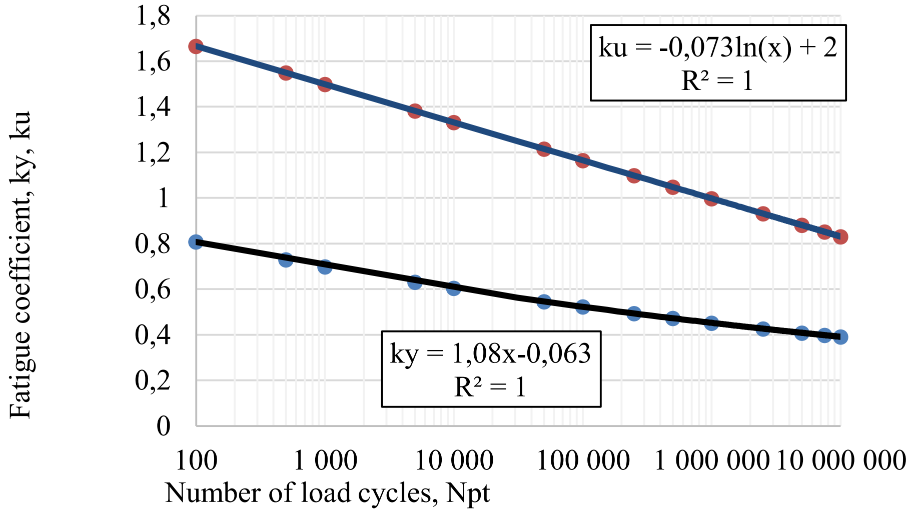

Figure 1 *– Dependence of fatigue coefficients k_y and ku on the number of load cycles N_{pt}*
Рисунок 1 *– Залежність коефіцієнтів втоми k_y та k_u від кількості циклів навантажень N_{pt}*

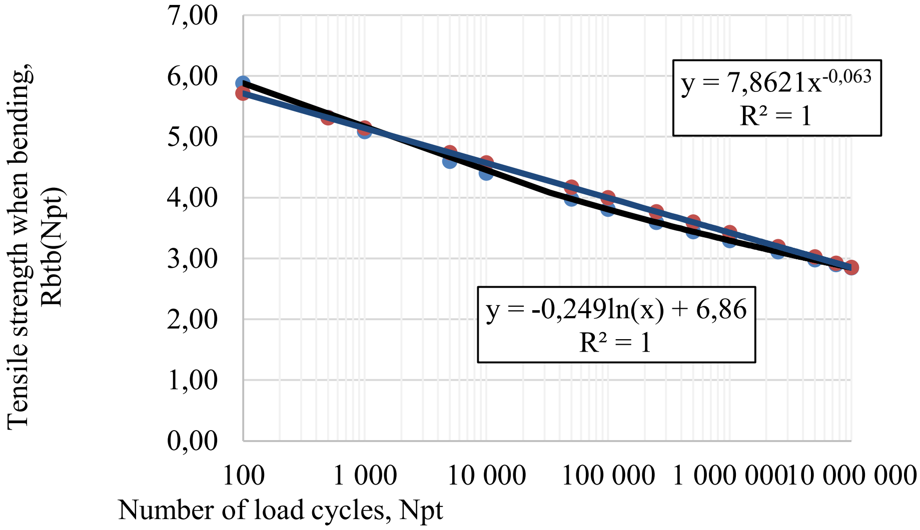

Figure 2 *– Dependence of ultimate fatigue strength $R_{btb}(N_{pt})$ on the number of loading cycles N_{pt}*
Рисунок 2 *– Залежність граничної міцності при втомі $R_{btb}(N_{pt})$ від кількості циклів навантажень N_{pt}*

Taking into account formulas (1 - 5) the number of cycles to failure (durability), is determined by the formula:

- for road pavements:

$$N_{pt} = R_{btb}\cdot(1+1{,}64V)K_F\cdot\left[\frac{1{,}08\cdot R_{btb}}{\sigma_{r\ i,eg\ \text{або}\ corn}}\right]^{15{,}873}\cdot{}'K_m, \tag{6}$$

- for airfield pavements:

$$N_{pt} = 10^{1/0{,}167\cdot\left[2-\frac{\sigma_{r\_i,eg,corrn}}{\gamma_c\cdot R_{btb}}\right]}. \tag{7}$$

Formulas (6) and (7) allow calculating the durability of road and airfield concrete pavements for stresses n arising from the action of loads at the center, edge, and corner of the slab.

Solution of the problem. For a theoretical assessment of a possible increase in deflection and, accordingly, a decrease in the total modulus of elasticity of the pavement due to mechanical damage to the pavement, Prof. B.S. Radovsky considered the effect of a through crack on the deflection of a slab resting on an elastic base [3]. A slab with a crack was considered as a semi-infinite slab loaded near the edge along a circular platform, and a slab without a crack – as unlimited under the same load. Deflections under the center of a loaded circular sites are determined according to Westergaard's formulas [4, 5, 6, 7]. As a result, an expression is obtained to find the ratio of deflections:

$$k_w = \frac{w_b}{w_c} = \frac{4}{\sqrt{3}}\left(\frac{2+1,2\nu}{1-\nu^2}\right)^{\frac{1}{2}} \frac{\left(1-(0.76+0.4\nu)\overline{R}\right)^2}{1-\frac{\overline{R}^2}{8\pi}\left(\ln\frac{12(1-\nu^2)}{\overline{R}^4}\right)+3)}, \qquad (8)$$

where parameter $\overline{R}$ equal:

$$\overline{R} = \frac{3}{4(h_1/D)\left[\frac{E_1(1-\nu_2^2)}{E_2(1-\nu_1^2)}\right]^{1/3}}, \qquad (9)$$

where w_b – deflection under the center of the loaded circular platform when loaded near the edge of the semi-limited slab on a Winkler base;

w_c – deflection under the center of the loaded circular platform on the pavement of the unlimited slab; h – plate thickness; E_1, E_2 and ν_1, ν_2 – respectively the modulus of elasticity of the material of the plate and the base and their coefficient of transverse deformation; P is the load.

According to the above formula, nomograms have been compiled, which make it possible to determine the effect of crack on the reduction of the bearing capacity of the structure of rigid and non-rigid road pavements in a wide range of changes in the input parameters E_1, E_2, h and D [4 -5].

Analysis the results of calculation.

For the analysis, the results of a specific calculation of the structure of the dry port cover under the action of a cover from a reach stacker weighing 100 - 120 tons were adopted. The equivalent load on one wheel is P=260 kN. Pressure in the pneumatics of the wheels is p=1.0 MPa. The diameter of the impression is D=0.575 m. The results of the analysis are given below (Fig. 3 – 5).

On the Fig. 5 change in the ratio of deflections are from the thickness of the slab for different modulus of elasticity of concrete E_1 (changes from the modulus of reinforced layers of 15000 MPa to the modulus of reinforced concrete E_1=45000 MPa) at the modulus of elasticity of the base E_2=150 MPa.

The deflection ratio does not increase linearly with an increase in the thickness of the slab and an increase in the modulus of elasticity of concrete. So, the calculation according to the formula (44) shows that with a change $\overline{R}$ from 0.1 to 0.4, the kw value changes from 2.7 to 1.3. Accordingly, if there is a through crack in the layers of the pavement and the base, then when loaded near it, the deflection increases by 1.3 - 2.7 times compared to rigid pavement without cracks, and to a greater extent, the lower the rigidity of these layers.

The modulus of elasticity of the base E_2 is of fundamental importance when its value is less than 160 - 250 MPa, where there is a transition from a rapid increase in deflection to its attenuation (Fig. 5). Which once again emphasizes the well-known fact about the need to provide a minimum modulus of elasticity under the surface of monolithic layers at the level of 120-150 MPa for roads.

For aerodrome pavements, as the analysis shows, the value of the modulus of elasticity of the base E_2 under the cement concrete slab, 180 – 250 MPa, depending on the load category and the thickness of the slab, is rational.

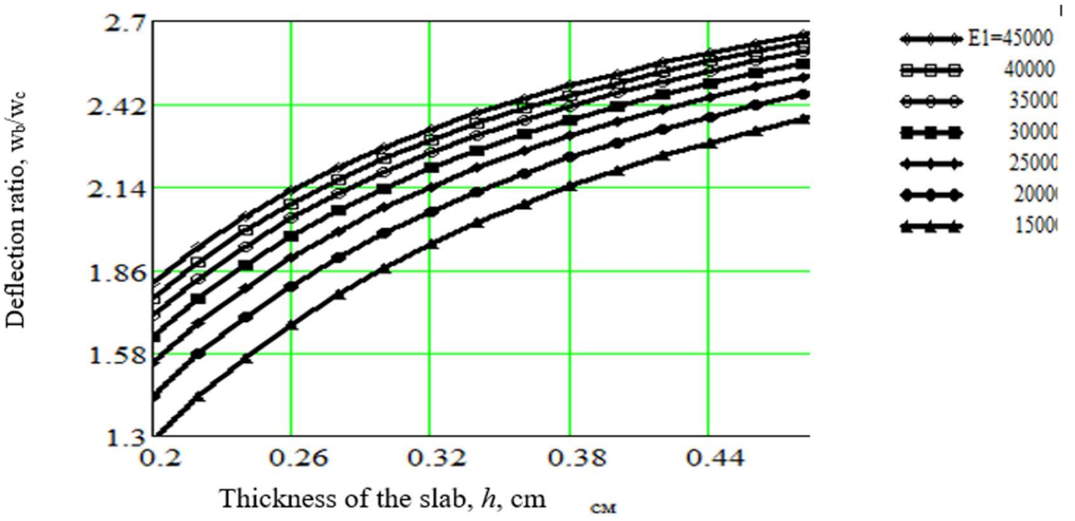

Figure 3 *– Change in the ratio of deflections*
Рисунок 3 *– Зміна коефіцієнта прогинів*

The analysis also shows that for each thickness of the pavement layer there is an optimal ratio between the modulus of elasticity of the pavement and the substrate, at which the ratio of deflections is minimal (Fig. 4).

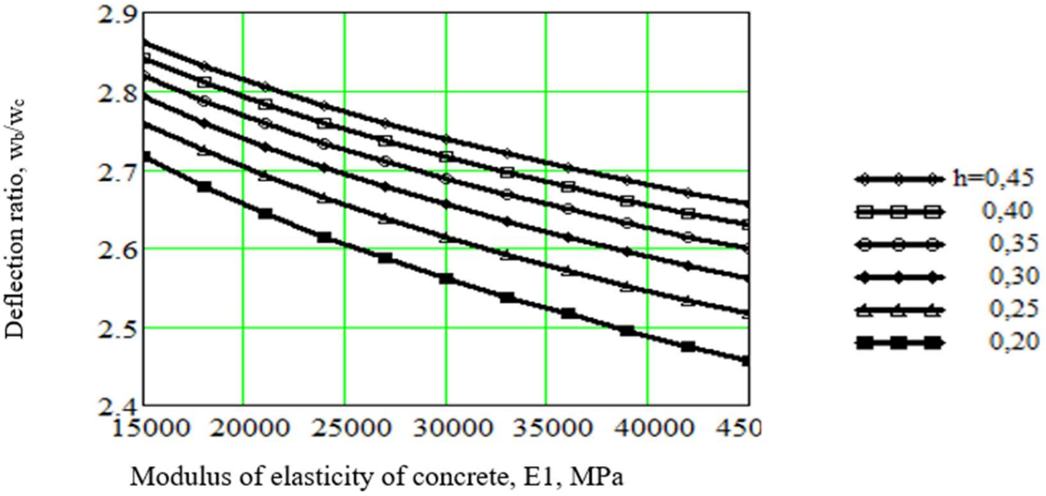

Figure 4 *– Change in the deflection ratio from the modulus of elasticity of concrete* E_1 *for the modulus of the base* E_2*=150 MPa at a slab thickness of 0.45, 0.40, 0.35, 0.30, 0.25 and 0.20 m, respectively*
Рисунок 4 *– Зміна коефіцієнта прогину від модуля пружності бетону* E_1 *для модуля основи* E_2*=150 МПа при товщині плити 0,45, 0,40, 0,35, 0,30, 0,25 та 0,20 м відповідно*

With an increase in the modulus of the base, the effect of cracking is less significant, which indicates the need to take into account the soil moisture of the roadbed when performing instrumental surveys of road pavement structures. An increase in the modulus of elasticity of the pavement leads to an increase in the effect of the crack on the decrease in bearing capacity.

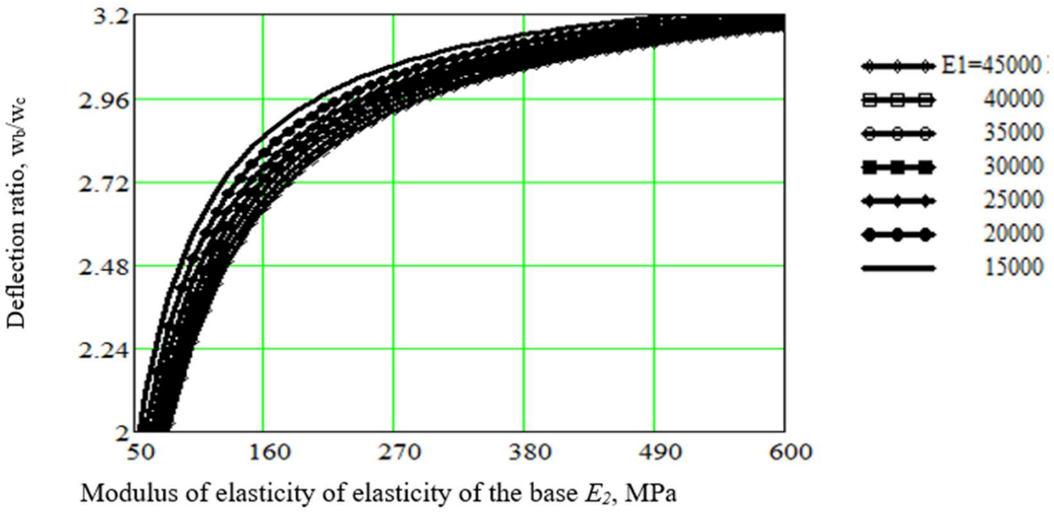

Figure 5 *– Change in the ratio of deflections depending on the modulus of elasticity of the base E2, varying from 50 MPa to 600 MPa with a plate thickness of 0,35 m.*

Рисунок 5 *– Зміна коефіцієнта прогинів залежно від модуля пружності основи E2, що змінюється від 50 МПа до 600 МПа при товщині плити 0,35 м.*

These results are quite consistent with the above experimental data.

In addition, the presence of destruction can be taken into account in the following ways:

1) due to a decrease in the thickness of the layer, similar to how it is done in SNiP 2.05.08.85;
2) due to a decrease in the modulus of elasticity of the pavement layer.

According to clause 5.68 of SNiP 2.05.08.85, when determining the stiffness and ultimate bending moment of concrete and reinforced concrete layers of pavement reinforcement, their design thickness t_{pd} should be taken depending on the category of destruction established according to Table. 25, and the thickness t_{ex} of the existing pavement at the destruction category:

$$\text{I} \rightarrow t_{pd}=t_{ex}; \quad \text{II} \rightarrow t_{pd}=0,9\cdot t_{ex}; \quad \text{III} \rightarrow t_{pd}=0,8\cdot t_{ex}. \qquad (10)$$

Existing rigid pavements of the IV category of destruction in the calculation should be taken into account as artificial bases with a bed coefficient *of* K_s = 600 MPa/m^3 (60 kgf/cm^3).

Given that during operation, the thickness of the concrete slab does not change in the presence of cracks, it is more logical to take into account the destruction due to a decrease in the distributive capacity of the slab, i.e. due to the modulus of elasticity of cement concrete. Then, for the above categories of destruction, given that the cylindrical rigidity of concrete and aroma concrete sections is determined by the formula:

$$B=\frac{E_b\cdot h^3}{12\cdot\left(1-\nu^2\right)}=0,085\cdot E_b\cdot h^3 \quad , \qquad (11)$$

Whence, equating to rigidity, it is obtained:

$$\text{I}\rightarrow E_{pd}=E_{ex}; \quad \text{II}\rightarrow E_{pd}=0,9^3\cdot E_{ex}=0,729\cdot E_{ex}; \quad \text{III}\rightarrow E_{pd}=0.8^3\cdot E_{ex}=0,512\cdot E_{ex}. \qquad (12)$$

When testing existing aerodrome structures, modern installations for measuring the deflection of falling cargo FWD or HWD should be used to establish real bearing capacity. The existing rigid pavements of the IV category of destruction will be taken into account in the calculation as artificial substrates with a characteristic value of the bedding coefficient:

$$K_{s\_aaa}=K_{s\_cp}\,(1-1,64\cdot V), \qquad (13)$$

where K_{s_cp} – is the average value of the modulus of elasticity or coefficient of the bed on the surface of the aerodrome pavements;

V – is the actual value of the coefficient of variation according to the test results.

In the first case, considering the effect of a defect in the form of a crack on the change in the cylindrical rigidity of the pavement, the transition coefficient K_h was obtained to calculate the decrease in the modulus of elasticity of a monolithic layer with cracks according to the formula:

$$K_h = \sqrt[3]{\frac{w_{in}}{w_{cr}}}, \tag{14}$$

where w_{in}, w_{cr} – respectively, the deflection of the pavement without defects and with defects that reduce its bearing capacity.

The equivalent thickness of the layer with h_{cr} defects will be determined by the formula:

$$h_{cr} = h_{in} \cdot K_h, \tag{15}$$

where h_{in} – the initial thickness of the monolithic layer.

$$K_E = \frac{w_{cr}}{w_{in}}$$

In the second case, to find the coefficient of reduction in the bearing capacity of the pavement using the formula (6.14 and 6.15) from [8]:

$$E^{(i)}_{заг} = \frac{\left[1{,}05 - 0{,}1\frac{h_i}{D}\left(1 - \sqrt[3]{E^{(i+1)}_{заг}/E_i}\right)\right]E_i}{0{,}71\sqrt[3]{\frac{E^{(i+1)}_{заг}}{E_i}}\,arctg\left(\frac{1{,}35h_{еке}}{D}\right) + \frac{E_i}{E^{(i+1)}_{заг}} \cdot \frac{2}{\pi}arctg\frac{D}{h_{еке}}}, \quad \text{where,} \quad \frac{h_{еке}}{D} = \frac{2h_i}{D}\sqrt[3]{\frac{E_i}{6E^{(i+1)}_{заг}}}, \tag{15}$$

where $E_1 = E_i$ – module of the pavement layer;

$E_2 = \mathrm{E}^{(i+1)}_{заг}$ – the modulus of the base under the cement concrete pavement;

$h = h_i$ – the thickness of the pavement layer;

D – the diameter of the wheel imprint, the formula is obtained:

$$K_E = K_T^{c\cdot\ln(h)-d}, \tag{17}$$

where K_T is a coefficient that takes into account a decrease in the modulus of elasticity of the cement concrete pavement as a result of cracking of the layer:

$$K_T = \frac{E_{cr}}{E_{in}}, \tag{18}$$

where $c = 0.3359 + 0.0001 \cdot E_2$; $d = 0{,}3093 + 0{,}0007 \cdot E_2$.

According to the proposed formula (18), for different values of the modulus of elasticity of the base and the thickness of the pavement layer, the values of the coefficient of reduction of the bearing capacity of the structure K_E were calculated at different values of the coefficient of reduction of the modulus of elasticity of the K_T pavement. For example, Fig. 6 shows the values of the coefficient of reduction bearing capacity of the structure for the thickness of the pavement layer of h = 20, 25, 30, 35, 40 and 45 cm with the modulus of elasticity of the base of 150 MPa.

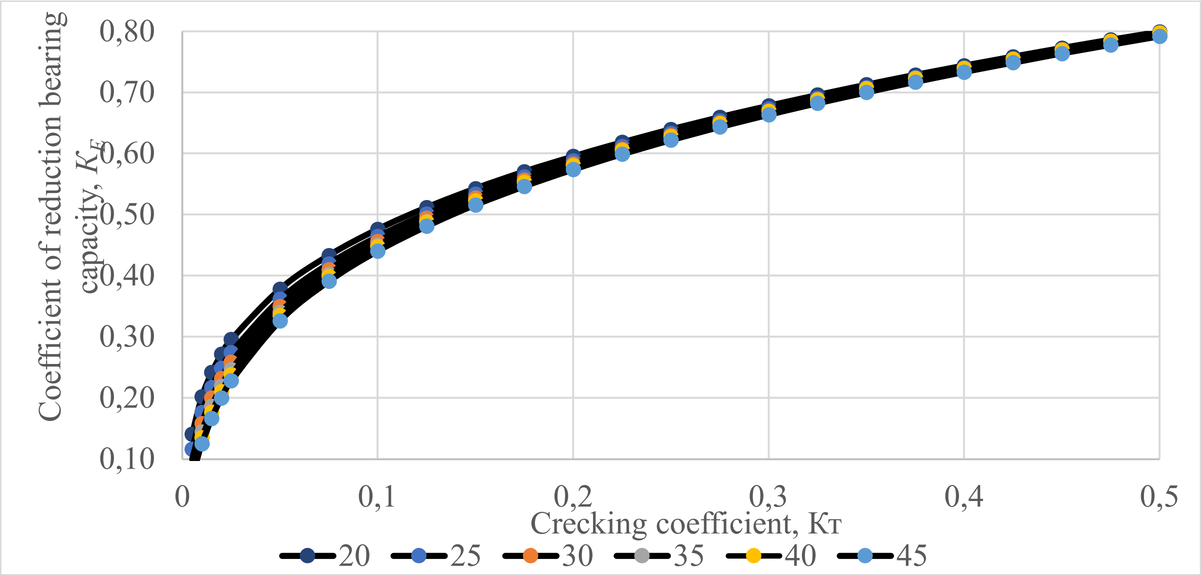

Figure 6 *- Estimation of the change in the coefficient of reduction of the bearing capacity of the pavement from the cracking coefficient of cement concrete for the modulus of elasticity of the base* E_2*=150 MPa*

Рисунок 6 - *Оцінка зміни коефіцієнта зниження несної здатності дорожнього та аеродромного покриття від коефіцієнта розтріскування цементобетону для модуля пружності основи* E_2*=150 МПа*

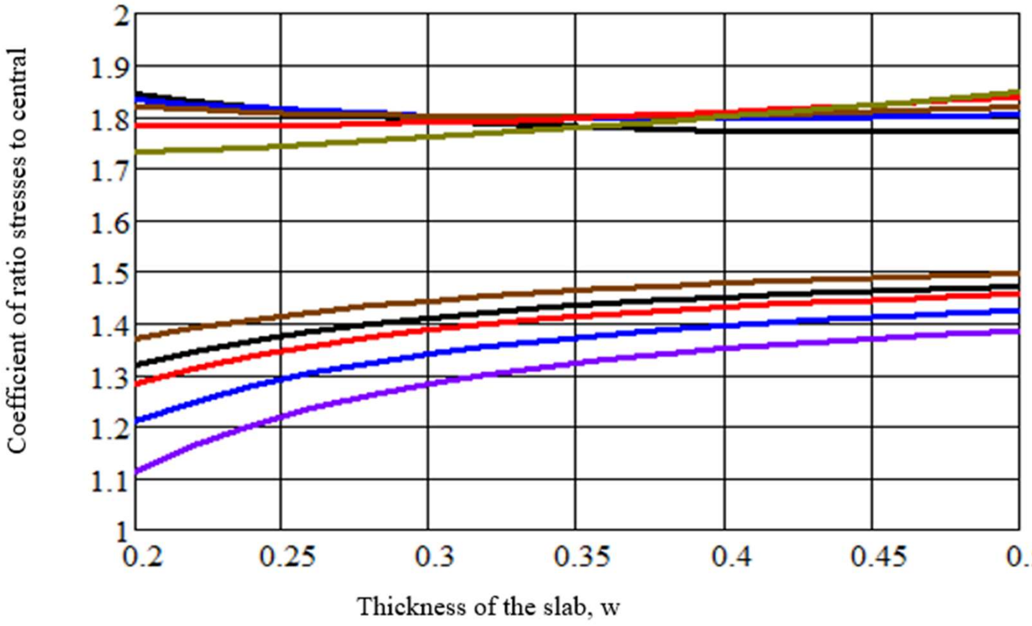

Figure 7 *– Change in the coefficient and* $K_{c\_i}K_{eg\_i}$ *depending on the thickness of the slab for the values of the coefficient of seeding 50, 100, 150, 300 and 600 MN·m/m*^{3}

Рисунок 7 *– Зміна коефіцієнта* K_{c_i} *та* K_{eg_i} *залежно від товщини плити для значень коефіцієнта висіву 50, 100, 150, 300 та 600 МН·м/м3*

The analysis of the change in the coefficient and $K_{c\_i}K_{eg\_i}$ depending on the thickness of the slab for the values of the bed coefficient of 50, 100, 150, 300 and 600 MN·m/m^3 is shown in Fig. 7.

As follows from Fig. 6 and 7 stresses at the corner exceed the stresses in the center of the slab, vary from 1,7 to 1,9 times (on average 1,8 times) and depend little on the coefficient of the bedding. Now it is clear why breakage of the corner of the slab occurs most often, in the absence of reinforcement, which is associated with an excess of stresses by 1,1 -1,6 times compared to the stresses at the edge of the slab, which is fixed in the norms.

Table 1 - *Effect of deformations on strength reduction (approximate reduction coefficients) in a wide range of changes in road pavement structures*

Таблиця 1 *- Вплив деформацій на зниження міцності (приблизні коефіцієнти зниження) в широкому діапазоні змін конструкцій дорожнього одягу*

Type of damage / destruction	Nature of the impact	Reduction factor		Notes
		bearing capacity K_E	durability K_d	
Hair (plastic) cracks ≤0.3 mm	Virtually no effect	0,95–1,0	0,9–0,95	Control; Sealing is not necessary
Shrinkage cracks 0.3–1 mm	Initial defects, accelerated moisture penetration	0,9–0,95	0,8–0,9	Sealing, thin-layer protection, ultra-thin pavements
Operational cracks 1–3 mm	Local Stiffness Reduction	0,85–0,9	0,7–0,8	Repair cracks, keys/staples as needed
Wide cracks >3–5 mm	Loss of solidity of the slab	0,7–0,8	0,5–0,6	Structural repairs/local repairs
Edge chipping, edge fracture	Reduced slab integrity, risk of fracture	0,75–0,85	0,6–0,7	Local replacement, edge reinforcement
Crumbling/falling out of pieces of concrete (spalling)	Violation of contact between the stove and the wheel	0,7–0,8	0,5–0,6	Repair with cards, polymer-repair mixtures
Oscillation/settling of slabs at the seams	Dynamic strokes, opening seams	0,65–0,75	0,5–0,6	Slab jacking, injection
Slab Lifting and Joint Fracture (≥6 mm)	Loss of load transfer	0,6–0,7	0,4–0,5	Restoration of seams, new dowels/staples
Concrete peeling/crumbling (delamination)	Violation of integrity, rapid progression	0,6–0,7	0,3–0,4	Milling, thin layer of wear/reinforcement
Corner breaks	High concentration of stresses at the corner	0,5–0,7	0,3–0,4	Inserts, dowels, local replacement of plates
Block cracks (transverse/longitudinal cracking)	Disability	0,4–0,6	0,2–0,3	Full/partial replacement of the stove
Crack mesh (crocodile skin)	Actual Loss of Bearing Capacity	0,3–0,5	0,2–0,3	Refurbishment/overhaul
Soaking slab breakdown (cracked slabs, stagnant water on the shattered slab pavement)	Actual Loss of Bearing Capacity	≤0,4	≤0,2	Refurbishment/overhaul

The coefficient characterizing the ratio of stress at the edge of the slab to the stress in the center of the slab K_{eg_i} varies from 1,1 to 1,5 and decreases with increasing base coefficient. So, for the 4th category of destruction during reconstruction (coefficient of 600 MN/m^3), you can take values from 1.1 for a slab thickness of 0,20 m to 1,4 for a slab thickness of 0,50 m.

Thus, on a theoretical basis, it is possible to establish a coefficient of reduction in the bearing capacity of the pavement depending on the factors of influence.

These values correspond well to the results of well-known experimental studies by various authors (Table 1 [3]) for durable pavement structures and [1-2] for roads of lower categories. That is, using the given dependencies (1-51), it is possible to take into account the influence of deformations on the reduction of strength in a wide range of changes in road pavement structures and changes in durability, taking into account the increase in stresses in different sections of the slab under different load schemes.

The coefficients of reducing the bearing capacity and durability of cement-concrete pavements depending on the type of damage and destruction are generalized (Table 1). They are formed on the basis of the experience of operation of roads and aerodromes (materials DBN B.2.3-4:2015, ICAO Annex 14, FAA AC 150/5320.

Explanation: φ_n is the multiplier to the calculated bearing capacity. For example, φ_n 0.7 means that the slab is operating at 70% of the design capacity.

φ_d is the coefficient of durability (the ratio of the actual resource to the standard).

The values are indicative, since specific values depend on: the thickness of the slab; base type; load intensity; climatic conditions (freeze-thaw cycles), etc.

For use in practical calculations (for example, when determining the degree of damage or when designing reinforcement layers), it is advisable to use these coefficients as corrective factors to the calculated moduli of elasticity or to the residual resource.

Conclusions

For currently common pavement structures, in the extreme case, for a rough assessment, it can be assumed that when the cracked pavement is loaded near the crack, the deflection is 3 times greater than further from it. At a distance of more than 1.5 ... 2.5 m from the crack, the deflection does not change compared to the original. Then, on average, the deflection increases by 2 times, and the average total modulus of elasticity of the pavement for areas with a destroyed pavement decreases accordingly due to destruction by about 2 times.

Based on the results of the calculations, it is recommended to multiply the calculated values of bending moments m_d, kN·m/m, per unit cross-sectional width of single-layer rigid pavements of all types by k — the transition coefficient from the bending moment at the central loading to the moment at the edge loading of the slab, which is assumed to be equal: for concrete and reinforced concrete pavements with butt joints or structural edge reinforcement — 1.2; for concrete and reinforced concrete pavements, which are arranged without butt joints and edge reinforcement of slabs - 1.4 - 1.5; for slab corners 1.7 -1.8; - for prefabricated pavements made of prestressed reinforced concrete slabs — 1.0; for reinforced concrete pavements with non-stressed reinforcement — according to Fig. 1 of the mandatory Annex 10 of SNiP 2.05.05 Aerodromes [1].

Assessment of the maximum possible change in the total modulus of elasticity of the road pavement due to destruction allows using the obtained coefficients to correct the degradation model according to the data of visual and instrumental inspection of structures. The materials of the work were used in the development of a classifier of defects in road pavements (a system for visual assessment of the condition of the pavement) and the development of a system for managing the condition of the pavement of roads and aerodromes. Based on the A manual for expert assessment of the condition of the pavement has been developed in order to establish the impact of defects and destruction on the change in the bearing capacity of road pavement structures.

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

Частина 2. Оцінка зміни коефіцієнта зниження несної здатності та деформативності дорожнього та аеродромного покриття

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 жосрткик дорожніх одягів на їх загальний модуль пружності та довговічність. Зазначається, що руйнування, спричинені транспортними засобами та погодними умовами, знижують модуль пружності дорожнього покриття. Дослідження, описані в статті, показують, що на пошкоджених ділянках доріг середній модуль пружності може бути в 1,9 раза нижчим, ніж на непошкоджених.

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 наявність наскрізної тріщини може збільшити прогин плити в 1,3-2,7 раза.

Автори дійшли висновку, що логічніше розглядати руйнування через зменшення модуля пружності цементобетону, а не через зменшення товщини шару. У статті також аналізується вплив модуля пружності основи на прогин плити. Оптимальне значення для автомобільних доріг з жорстким покриттям становить 140-180 МПа. Запропоновано формулу для розрахунку коефіцієнтів приведення до еквівалентної несної здатності за руйнування у вигляді відколів кутів та країв плит.

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

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