Refined assessment of strength of concrete pavement probabilistic method

A P Stepushin, I V Chistyakov, M G Goryachev, Y S Sadovnikova, A K Kyaing

Moscow Automobile and Road Construction State Technical University (MADI), 125319, Leningradsky prospekt, 64, Moscow, Russian Federation

Email: fumo@madi.ru

Abstract. The object of research is the method of calculating the strength of cement concrete airfield pavement. According to the current regulatory documents, the calculation of the strength of the coating is carried out according to the first limit state, taking into account the internal forces arising in the slab from the impact of the wheel load and temperature. The repeated impact of loads from the wheels of the main supports of various types of air is replaced by the influence of the main support of the heaviest aircraft, causing the greatest bending moment in the design section of the plate. However, the calculations do not take into account the stochastic nature of such factors as the take-off weight of aircraft, the plate thickness, the bed ratio of the elastic foundation, the probability of the combined effect of operating loads from the main bearing wheels and temperature in the calculated section of the plate, as well as the probability distribution of loads from the aircraft spectrum across the width of the airfield elements. The article proposes a method for taking into account the probabilistic-statistical variability of operating loads, physical and mechanical properties of materials and the geometric characteristics of the plate, recommended when developing a new regulatory framework for the design of rigid airfield pavements. The method of statistical linearization of random functions of several random arguments was chosen as the research method. Using the mathematical apparatus of the theory of random functions, the statistical coefficient of the working conditions of the plate is analytically determined, and a numerical analysis of the obtained analytical solution is carried out. It has been established that with the same unfavorable combination of variability of basic arguments, the calculated absolute value of the statistical coefficient of the working conditions of the slab is more influenced by the coefficient of variation of the slab thickness than the coefficient of variation of the strength of cement concrete in bending. The condition for calculating the required thickness of the hard airfield slab of monolithic cement concrete is determined.

1. Introduction

The article describes the analysis of current practice used in Russian Federation and in the CIS countries for new concrete pavements design and evaluation. According to the specification [1] concrete pavements are designed to serve a predicted number of load applications for twenty years at the lowest possible initial and maintenance costs. The main criteria for design of concrete slabs thickness is cracking initiated by aircraft wheel gears and thermal stresses. Repeated loading from the traffic mixture is converted into a single design aircraft. The design aircraft is determined as the most damaging heavy airplane. All annual departures of the traffic mixture are converted to equivalent number of annual
departures of the design aircraft. Thickness design specification [1,2,3] reflects only a realistic degree of variation in flexural strength of concrete applying 95% confidence level and thermal stress about 0.05…0.07 MPa considering its different signs during daily and night periods and decreases due to subbase restraint stress. Existing procedure does ignore stochastic nature of other main variables: aircraft takeoff weight, airplane traffic wander, in-situ slab thickness, elastic modulus of concrete, modulus of subgrade reaction and climatic inputs causing thermal bending moments in the concrete and probability of its combined effect with bending moment in slab under traffic loadings expected from specific volume of mixed traffic and its distribution pattern.

The analysis of concrete pavements performance life shows that real serviceability age at civilian airports of Russian Federation and in the CIS countries differ from 3 to 30 years [4-8]. One of the reasons of such deviation in the concrete performance life may be ignoring of the stochastic nature of the design inputs in the previous deterministic design guides. Consequently, it is necessary to develop the current methodology for calculating rigid airfield pavements based on mathematical methods of the reliability theory, as was done in [9–12]. The purpose of this article is to summarize the methodology for calculating cement concrete pavement during its design and assessment of the carrying capacity.

2. Methods

Deterministic design procedure includes comparison of bending moments caused by aircraft loads at the outside edge of a concrete pavement and ultimate bending moment for given slab thickness using the following equation:

\[ d_d \leq d_1 \cdot z, \]  \hspace{1cm} (1)

where \( z \) – factor to convert bending moment increase at the outside edge; \( d_1 \) – bending moment in concrete slab caused by design aircraft main gear wheels at the interior of the slab; \( d_d \) – bending moment in concrete slab caused by the design aircraft main gear arrangement at the outside edge of slab:

\[ d_d \leq d_2 \cdot z \]  \hspace{1cm} (2)

where \( m_2 \) – ultimate bending moment for given slab thickness, flexural strength of concrete at design age and number of load repetitions:

\[ d_i = \frac{\gamma_2 \cdot R_{bub} \cdot h^2}{6} \]  \hspace{1cm} (3)

where \( \gamma_2 \) – factor to convert concrete strength increase with age and warping stresses which was not changed since 1960 year till nowadays (table 1), \( R_{bub} \) – design modulus of rupture; \( h \) – slab thickness.

The results of flexural fatigue research under continued repetitions of loads failure of concrete beams occur at stresses ratios of less than unity. Flexural fatigue of concrete is reflected in specification [1] by selection of load repetition factor \( z_1 \) based on the number of the heaviest aircraft under carriage wheel passes expected during the pavement design life which is supposed to be equal to 20 years:

\[ z_1 = 2 - \frac{\log L}{6}, \]  \hspace{1cm} (4)

where \( L \) – expected number of the heaviest aircraft main gear wheel load applications for design age of the pavement.

It should be noted that equation (4) corresponds to PCA (Portland Cement Association) fatigue model results published in 1973 [13-18] and may be expressed as follows:

\[ Z_i = \frac{\gamma(N)}{\gamma(N=1-10^6)} = \frac{\gamma(N)}{0.5} \]  \hspace{1cm} (5)

where \( Z_i \) – load repetition factor to reflect fatigue effect in the concrete under repeated loading; \( \gamma(N) \) – stress repetition ratio for \( N_i \).

\[ \gamma(N) = \frac{\sigma_{N_i}}{R} = 1 - \frac{\lg(N)}{12} \]  \hspace{1cm} (6)
where $\sigma_{N_i}$ - repetitive stress; $R$ - mean flexural strength of concrete; $N$ - number of repetitions to cause concrete flexural fatigue failure; $\gamma(N = 1 \cdot 10^6) = 0.5$ - stress ratio permitting $1 \cdot 10^6$ load repetitions without loss of fatigue resistance of plain cement concrete in flexure test.

From equation (6) one can calculate the number of repetitions $N_i$ to cause flexural rupture under stress $\sigma_{N_i}$:

$$N_{\sigma_{N_i}} = 10^{12(1-\gamma(N))}.$$  \hspace{1cm} (7)

Under real pavement performance conditions, stress ratio of concrete depends on stochastic nature of design variables which effect on the bending moments in the slab.

Suggestions proposed here where developed from a study and correlation of the existing design procedures [1], statistical analysis of aircraft centerline deviations on runway and taxiway that were collected in reports [19-36], plate theory [13-19], Miner’s fatigue law and theory of stochastic functions [36]

The equation (1) may be rewritten in the form:

$$(\overline{d}_F + \overline{d}_T) \cdot P_T \leq z_1 \cdot \overline{d}_T,$$  \hspace{1cm} (8)

where $\overline{d}_F$ - average bending moment under main gear wheels loading calculated by formula (2); $\overline{d}_T$ - average bending moment caused temperature calculated by the following equation [18]:

$$\overline{d}_T = 0.0437 \alpha \cdot h^2 \cdot E_b \cdot Q,$$  \hspace{1cm} (9)

where $\alpha$ - coefficient of thermal expansion of concrete: $\alpha = 0.00001$; $h$ - slab thickness; $E_b$ - modulus of elasticity of concrete, Pa; $Q$ - average difference in temperature between the top and bottom surfaces of the slab during design period (spring or autumn); $P_T$ - probability to reflect the combined effect of the functions $\overline{d}_F$ and $\overline{d}_T$ on the summary bending moment in the slab under consideration.

### Table 1. Values of $\gamma_2$ according to specifications

| Pavement Sections | Values of $\gamma_2$ according to Specifications |
|-------------------|-----------------------------------------------|
|                   | Construction standards 120-60 | Construction standards 120-70 | Construction Norms and Regulations11-47-80 | Construction Norms and Regulations 2.05.08-85 Set of rules 121.133.2012 |
| Taxiways          | 0.8 | 0.8 | 0.8 | 0.8 |
| The ends of runways L= 150 m | 0.9 | 0.8 | 0.8 | 0.8 |
| Subdivisions of runway pavements $L_{RUNWAY}/4$ – 150 m, connecting to the runway ends | 0.9 | 0.9 | 0.9 | 0.9 |
| Runway middle pavement section | 0.9 | 0.9 | 0.9 | 0.9 |
| Edge parts of the runway middle pavement section | 1.1 | 1.1 | 1.1 | 1.1 |
| Exits, aprons and other | 0.9 | 0.9 | 0.9 | 0.9 |
\[
P_{Ft} = P(d_F + d_t) - P(d_F) \cdot P(d_t),
\]

(10)

where \(P(d_F)\) – probability of the mean bending moment under main gear wheels; \(P(d_t)\) – probability of the mean thermal bending moment;

\[
P(d_F) = P(d_t) = 0.5, \text{ so by (9) } P_{Ft} = (0.5 + 0.5) - 0.5 \cdot 0.5 = 0.75,
\]

where \(d_t\) – mean ultimate bending moment caused by designed gear load. \(Z_2\) – parameter to adjust stochastic nature of the design inputs and design reliability of the concrete pavement [18]:

\[
Z_2 = 1 - \sqrt{1 - (1 - Z_2^2 \cdot V_z^2)(1 - Z_2^2 \cdot V_{dl}^2)}
\]

(11)

where \(Z_2\) – statistical coefficient to account cumulative effects of variability of the takeoff weights of the airplanes, number of the full-load applications, flexural strength and modulus of elasticity of concrete, modulus of subgrade reaction, in-situ pavement slabs thicknesses, surface pavement temperature amplitude and design reliability; \(Z_s\) – standardized normal variant for \(P\) level of pavement reliability; \(d_{\text{ult}}\) – variance of bending moment caused by designed gear load; \(D_{\text{ult}}\) – variance of bending moment due to temperature gradient between top and the bottom surfaces of slab

\[
D_{db} = \left( \frac{\partial D_E}{\partial d_F} \right)^2 \cdot S_d^2 + \left( \frac{\partial D_E}{\partial E_b} \right)^2 \cdot S_{E_b}^2 + \left( \frac{\partial D_E}{\partial h} \right)^2 \cdot S_h^2 + \left( \frac{\partial D_E}{\partial Z_s} \right)^2 \cdot S_z^2
\]

(12)

\[
D_{dt} = \left( \frac{\partial d}{\partial t} \right)^2 \cdot S_t^2 + \left( \frac{\partial d}{\partial E_b} \right)^2 \cdot S_{E_b}^2 + \left( \frac{\partial d}{\partial Q} \right)^2 \cdot S_Q^2
\]

(13)

\[
V_{dl} = \frac{\sqrt{D_{dl}}}{d_t}
\]

(14)

\[
D_{D_1} = \left( \frac{\partial D_1}{\partial R} \right)^2 \cdot S_{R}^2 + \left( \frac{\partial D_1}{\partial h} \right)^2 \cdot S_h^2 + \left( \frac{\partial D_1}{\partial L} \right)^2 \cdot S_l^2
\]

(15)

where \(d_F\) – average bending moment in concrete stab caused by the design aircraft main gear wheels; \(S_{d_F}, S_{E_b}, S_h, S_{Z_s}, S_{Q}, S_{R}, S_l\) – standard deviations of wheel load, modulus elasticity of concrete, slab thickness, modulus of subgrade reaction, amplitude of temperature, flexural strength of concrete and number of load applications; \(\frac{\partial D_E}{\partial d}\) – first partial derivative of stochastic function of bending moments with respect to the means of random variables: wheel load \(F_d\) modulus of elasticity of concrete \(E_b\) thickness of slab \(h\), modulus of subgrade \(Z_s\), amplitude of pavement surface temperature \(Q\), flexural strength of concrete \(R\) and number of load applications \(L\):

\[
\frac{\partial D_E}{\partial F_d} = 0.018306 \sqrt{\frac{P_Q}{F_d^3} \cdot 4 \cdot h^3 E_b / Z_s}
\]

(16)

\[
\frac{\partial D_E}{\partial E_b} = 0.001749 \sqrt{h^3 / Z_s E_b^3} - 0.013745 \frac{4 h^3}{Z_s E_b^7}
\]

(17)

\[
\frac{\partial D_E}{\partial h} = 0.0113745 \sqrt{P_Q F_d} \cdot 4 E_b h^5 / Z_s + 0.005248 P_Q E_b / h Z_s
\]

(18)
\[
\frac{\partial D_{E}}{\partial Z_{s}} = 0.022908 \sqrt{\frac{E_{b}^{4} b^{2}}{4 h^{3}}} / Z_{s}^{9} - 0.005247 P_{Q} \sqrt{E_{b}^{3}} / Z_{s}^{5}
\]  
(19)

\[
\frac{\partial D_{1}}{\partial h} = 0.0874 E_{s} \alpha Q h
\]  
(20)

\[
\frac{\partial D_{1}}{\partial E_{b}} = 0.0437 \alpha Q h^{2}
\]  
(21)

\[
\frac{\partial D_{1}}{\partial Q} = 0.0437 \alpha E_{b} h^{2}
\]  
(22)

\[
\frac{\partial D_{1}}{\partial R} = \alpha_{1} h^{2} (2 - \log L / 6)
\]  
(23)

\[
\frac{\partial D_{1}}{\partial h} = 2 \alpha_{1} R h (2 - \log L / 6)
\]  
(24)

\[
\frac{\partial D_{1}}{\partial L} = -0.0724 \alpha_{1} R h^{2} / L
\]  
(25)

where \( \bar{D} \) – average bending moment due to temperature gradient between top and the bottom surfaces of slab; \( \bar{D}_{u} \) – average ultimate bending moment computed for given slab thickness and design modulus of rupture of the concrete; \( \alpha_{1} \) – parameter to convert concrete flexural strength increase with age.

3. Results and Discussion

In order to investigate the influence of statistical variability of design parameters and given probability level on the concrete pavement functional life numerical analysis was performed under following conditions: concrete slab thickness \( h = 0.3 \) m; coefficient of variation of slab thickness \( V_{h} = 0.10 \); average flexural strength of concrete \( R = 5.13 \) MPa; coefficient of variation of concrete flexural strength \( V_{R} = 0.135 \); average modulus elasticity of concrete \( E_{b} = 3.24 \cdot 10^{4} \) MPa; coefficient of variation of modulus of elasticity of concrete \( V_{E} = 0.135 \); average coefficient of subgrade reaction \( Z_{s} = 51.6 \) MH/m²; coefficient of subgrade reaction \( V_{Z} = 0.30 \); average amplitude of concrete surface pavement temperature \( Q = 7.55 \) °C; coefficient of variation of amplitude \( V_{Q} = 0.33 \); aircraft average take-off mass \( D = 206 \) t; coefficient of take-off mass variation \( V_{D} = 0.55 \); average daily departures \( U_{i} = 60 \); coefficient of daily take off number variation \( V_{1} = 0.10 \); number of tandem axes – 2; probability of main wheels passes \( P_{i}(x) = 0.83 \).

Values of parameter \( K_{2} \) calculated by formulas (11) – (25) are given in the table 2.

| Parameter                  | Values |
|----------------------------|--------|
| Design reliability level   | 0.5    | 0.6    | 0.7    | 0.8    | 0.9    |
| Parameter \( Z_{2} \)      | 1.0    | 0.95   | 0.90   | 0.84   | 0.77   |

To account the stochastic nature of the design inputs and considering (8) the equation (7) may rewritten as follows

\[
N_{\sigma_{s_{n}}} = 10^{2(1-P_{n}) \left( \frac{\bar{D}_{1} + \bar{D}_{u}}{Z_{s} D_{1}} \right)}
\]  
(26)
where $D_f$ – mean of bending moment in concrete slab caused by the wheels of main gear arrangement; $D_t$ – mean of bending moment due to temperature gradient between the top and the bottom surfaces of slab; $D_1$ – mean of ultimate bending moment computed for given slab thickness and design modulus of rupture of concrete; $Z_2$ – statistical coefficient to account combined effect of variability of wheel loads, number of load repetitions, flexural strength and modulus of elasticity of concrete, modulus of subgrade reaction, thickness of slab and surface pavement temperature amplitude (11).

Detrimental effect $D$ caused by load applications $N_i$ may be calculated by formula

$$D = \frac{1}{N_{\sigma_{ni}}} = \frac{1}{10^{12(1-p_n)(\frac{D_f+D_t}{Z_2D_1})}}$$

(27)

In common summary detrimental effect $D$ under repetition cycles of special aircraft traffic mix pattern is expressed by Miner’s law [31]

$$\sum_{i=1}^{n_{\sigma_i}} \frac{N_{\sigma_i}}{N_{\sigma_i}} = 1$$

(28)

where $N_{\sigma_i}$ – number of stress repetitions at outside edge of slab for $i$-th aircraft main undercarriage wheels for the design life may be calculated as follow

$$N_{\sigma_i} = n(365-T_f) \sum z_{n_i} \cdot n_1 \cdot U_i \cdot P_i(x)$$

(29)

where $n$ – design life of the concrete pavement; $T_f$ – number of days in the year when subgrade is in frozen condition; $z_{n_i}$ – coefficient to convert the effect of particular aircraft to the effect of undercarriage assembly of the design aircraft; $n_1$ – number of tandem gears in undercarriage assembly of the particular aircraft; $U_i$ – number of daily departures of particular aircraft; $P_i(x)$ – probability to account lateral movement (airplane wander) and particular airplanes main gear and configurations on the transverse distribution of load applications on the pavement at the anticipated facility;

$$P_i(x) = P(x_1 \cdot x_2 \cdot x_3) = \sum_{x_1} f(x, x_1, S_{x_1})$$

$$f(x, x_1, S_{x_1}) = \frac{1}{S_{x_1} \sqrt{2\pi}} e^{-\frac{(x-x_1)^2}{2S_{x_1}^2}}$$

(30)

(31)

$$x_1 = x - \frac{b}{2}$$

$$x_2 = x + \frac{b}{2}$$

(32)

where $f(x, x_1, S_{x_1})$ – normal distribution function; $x_i$ and $S_{x_i}$ – mean and standard deviation of aircraft wheel paths from pavement centerline or guideline marking; $x$ – distance from longitudinal axis (centerline or guideline marking) of pavement to design section of slab, where load repetitions are determined; $b$ – design traffic width

$$b = d + 2R_i$$

(33)

where $d$ – distance between centers of contact areas of dual wheels; $R_i$ – radius of main undercarriage wheel contact area for specific aircraft

$$R_i = \sqrt{\frac{F_d}{\pi \cdot P_Q}}$$

(34)

$$F_{di} = \frac{D_f \cdot g \cdot z'}{n \cdot n_w} Z_g Y_f$$

(35)

where $F_{di}$ – wheel load, $N$; $g$ – acceleration of gravity; $z'$ – percent of the maximum anticipated takeoff weight of the airplane on the main landing gears; $z_d$ – parameter to account dynamic impact of
the airplane main gears wheels on the pavement; $\gamma$ – parameter to reflect wings lift; $n'$ – number of main undercarriage assemblies; $n_w$ – number of wheels in undercarriage assembly.

Substitution formula (29) to (26) gives following equation to determine anticipated life of concrete pavement

$$n = \frac{10}{(365 - T_f)} \sum_{i=1}^{k} Z_{n_i} \cdot n_{1i} \cdot u_i \cdot P_i(x)$$  \hspace{1cm} (36)

Proposed equation allows more precisely evaluate number of load applications expected during pavement life from specific volume of mixed traffic, its distribution pattern, variability of flexural strength and elastic modulus of concrete, modulus of subgrade reaction, slab thickness, mean amplitude of surface pavement temperature, number of stress repetitions and design reliability level of pavement structure.

In order to reduce the complexity of calculating the statistical coefficient of $K_2$ working conditions using formula (11), a program for calculating “STK” was developed.

The program “STK” provides for printing the statistical coefficient of working conditions at a given level of reliability $P = 0.5 \ldots 0.95$ and the initial calculation data. The results of the calculation with the following initial data are given in table 3.

**Table 3. The results of the calculation**

| Parameter                                      | Value | Unit  |
|-----------------------------------------------|-------|-------|
| Road-climatic zone                            | 2     |       |
| Type of hydrogeological conditions            | 2     |       |
| Soil of natural base                          | sandy loam |       |
| The average value of the bedding ratio of the soil base | 50    | MN/m3 |
| The coefficient of variation of the bedding coefficient of the soil base | 0.30  |       |
| The average value of the load on the wheel    | 170   | kN    |
| The coefficient of variation of the load on the wheel | 0.05  |       |
| Internal tire pressure                        | 1.0   | MPa   |
| The average strength of cement concrete in tensile bending | 5.12  | MPa   |
| Coefficient of variation cement concrete strength under bending tension | 0.135 |       |
| The average value of the modulus of elasticity of cement concrete | 32400 MPa |       |
| The coefficient of variation of the modulus of elasticity of cement concrete | 0.135 |       |
| The average number of applications loads      | 20000 |       |
| The coefficient of variation of the number of applications loads | 0.20  |       |
| The average value of the amplitude of temperature fluctuations on the surface of the cement concrete | 10    | °C    |
| The coefficient of variation of the amplitude of temperature fluctuations | 0.30  |       |
The average value of the plate thickness 0.16…0.30 m
The coefficient of variation of the thickness of the plate 0.05
The value of the estimated coefficients: zd=1.20.

It is shown that functional life of concrete pavements depends on statistical variability of mechanical properties of materials, aircraft traffic mix loads and environmental condition. That is why to predict pavement service life till cracking of concrete due to fatigue consumption will take place can be implemented only with certain probability [37-39]. Procedure proposed in this paper may be considered as first step towards statistical approach in that direction. Similar results in the calculation of building structures can be noted in [3,12,16,22]. However, in the data, the work does not take into account the specifics of the functioning of aerodrome coatings using coefficients characterizing stochastic operating loads. The results of that approach also underline the significance of quality control and statistical evaluations of test data of construction materials used for a particular airport pavement’s project in situ. The use of statistical approach provides more realistic data to the cost estimator for a new particular project or pavement overlay design [31, 35, 36]. Probability distribution pattern for different traffic mix and statistical coefficient values, calculated for various regions of Russian Federation and in the CIS countries are proposed for adjustment to aerodrome’s construction rules and to modify existing deterministic method [1].

It is important to note that functional pavement life define the moment of initial process of cracking caused by stress repetitions in a critical traffic width where the probability of design aircraft main leg wheels passes is maximum. That is why procedure proposed here requires modification to reflect cracking propagation in concrete slabs after initial cracks have developed. In addition it is of interest to compare numerical value of functional life received by statistical approach to real serviceability age of concrete pavements designed by conventional deterministic methodology.

4. Conclusion
1. The article defines the statistical coefficient of the working conditions of the plate taking into account the operational loads, physical and mechanical properties of materials and the geometric characteristics of the plate.
2. The statistical coefficient of the working conditions of the plate at a given level of reliability for different values of the plate thickness was calculated.
3. Proposed to use the condition (2) for calculating the required thickness of the hard airfield slab coating of monolithic cement concrete.
4. The comparison of the calculated values of the statistical coefficient of the conditions of hard airfield pavements with those adopted in Set of rules 121.133302 shows that the standard coefficient of working conditions γ_2= 0.80 for groups of sections of group A of cement concrete pavements of aerodromes located to the north of 50° north latitude corresponds to the specified level of reliability P = 0.80 for plates with a thickness of 0.16…0.22 m and P <0.80 for plates with a thickness of 0.24…0.30 m.
5. Implemented statistical analysis showed that mean serviceability age of concrete pavements in Russian Federation airports is 11 years. That result has a good compromise with statistical approach [37-39] using suggested form (33) at desired probability level P=0.95.

Reference
[1] SP 121.13330.2012 2012 Aerodromy. Aktualizirovannaya redaktsiya SNiP 32-03-96. [Airfields. Updated edition of Construction Rules and Regulations 32-03-96]. (Moscow: Analitik) p. 97.
[2] Klekovkina M P 2016 Sostoyaniye i nedostatki konstruirovaniya i rascheta dorozhnykh odezhd s tsementobetonnym pokrytiyem [The state and shortcomings of the design and calculation
of pavement with cement concrete pavement] Vestnik grazhdanskikh inzhenerov 1(54) 136-140.

[3] Shvabyuk V I, Rotko S V, Matkova A V 2016 K probleme sovershenstvovannogo rascheta izgotovleniya plit na zhestkom i elasticheskom osnovaniyakh [To the problem of the improved calculation of the manufacture of plates on rigid and elastic bases] Naukoví notatki 54 376-380.

[4] Carpiuc-Prisacari A, Poncelet M, Hild F, Leclerc H, Kazymyrenko K 2017 Comparison between experimental and numerical results of mixed-mode crack propagation in concrete: influence of boundary conditions choice Cement and Concrete Research 100 329-340.

[5] García V J, Zúñiga-Suárez A R, Zúñiga-Torres B C, Villalta-Granda L J, Márquez C O 2017 Brazilian test of concrete specimens subjected to different loading geometries: review and new insights International Journal of Concrete Structures and Materials 11(2) 343-363.

[6] Corrado M, Molinari J-F 2016 Effects of residual stresses on the tensile fatigue behavior of concrete Cement and Concrete Research 89 206-219.

[7] Wei Wu, Jianwu Wang, Chao Zhang, Qingkun Yu 2015 Research on method of the heavy traffic airport cement concrete pavement thickness design, In Proceedings of International Conference on Materials, Environmental and Biological Engineering (Paris: Atlantis Press) pp. 521-424.

[8] Bažant Z P 2002 Concrete fracture models: testing and practice Engineering Fracture Mechanics 69(2) 165-205.

[9] Chen X, Chen C, Xu L, Shao Y 2017 Dynamic flexural strength of concrete under high strain rates Magazine of Concrete Research 69(3) 109-119.

[10] Gameliak I, Vyrozheymskiy V, Voloshyna I, Dmitriev M 2016 Research of cement concrete pavement using thermal imaging method. functional pavement design, In Proceedings of the 4th Chinese-European Workshop on Functional Pavement Design (Netherlands: CRC Press) pp. 1489-1498.

[11] Tang S W, Li Z J, Yao Y, Andrade C 2015 Recent durability studies on concrete structure Cement and Concrete Research 78 143-154.

[12] Jeong M G, El-Basyouny M 2010 Statistical applications and stochastic analysis for performance-related specification of asphalt quality assurance Transportation Research Record 2151 84-92.

[13] Stepushin A P 1985 Primenenije metodov teorii sluchaynykh funktsiy k opredeleniyu nesushchey sposobnosti plity armobetononogo pokrytiya [Application of the methods of the theory of random functions to the determination of the bearing capacity of the slab of reinforced concrete pavement] Sbornik nauchnykh trudov MADI 1985 20-33.

[14] Stepushin A P 2016 Naturnyye ispytaniya tsementobetonogo pokrytiya [Field tests of cement concrete pavement] Vestnik MADI 4(47) 98-102.

[15] Stepushin A P, Saburenkova V A 2017 Nadezhnost tsementobetonykh pokrytiy aerodromov [Reliability of cement concrete coatings of airfields] Vestnik MADI 1(48) 84-89.

[16] Ushakov V V, Yarmolinsky V A, Dobrov E M, Goryachev M G, Lugov S V 2017 Revision of descriptions and calculated properties of road bed soils and asphalt concrete materials upon designing of highway pavements in terms of criteria of residual deformations and fatigue cracking of asphalt concretes International Journal of Civil Engineering and Technology 8(9) 1074-1083.

[17] Van-Hieu Nguyen, Duy-Dong Nguyen, Tatarinov V 2018 Methods of spectral density estimation for airfield pavements MATEC Web of Conference 251 9.

[18] Guide for design of aerodromes 2005 Part 3. Pavements. ICAO Doc. 9157 – AN/ 901. (Montreal: ICAO) p. 349.

[19] Nosov V P, Dobrov E M, Chistyakov I, Borisiuk N V and Fotiadi A 2017 Mathematical modelling of cracking process in concrete pavement highways International Journal of Applied Research 12(23) 13158-13164.
[20] Ushakov V V, Nosov V P, Yarmolinsky V A, Goryachev M G, Lugov S V 2016 Setting frequency of works on the arrangement of wear and protective layers of road surfaces. *International Journal of Applied Engineering Research* 11(23) 11207-11214.

[21] Kiselev V P, Filimonov V S, Bugaenko M B, Kemenev N V, Ivanova L A 2013 Improving the quality of polymer-modified asphalt coating binder by settling resin of pyrolysis *SibFU Journal. Engineering and Technologies* 6(8) pp. 895-902.

[22] Paccard R G 1973 *Design of concrete airport pavement* (Illinois: Skokie, Portland Cement Association) p. 61.

[23] Ashford N, Wright P H 1984 *Airport Engineering* (Wiley-Interscience Publication: New York) p. 433.

[24] Zhang J, Weng X, Qu B, Liu J, Yang B, Li Y 2018 Failure modes and mechanisms of pavements in saline foundations *Proceedings of the Institution of Civil Engineers: Transport* 171(3) 174-182.

[25] Sassani A, Ceylan H, Kim S, Arabzadeh A, Taylor P C, Gopalakrishnan K 2018 Development of carbon fiber-modified electrically conductive concrete for implementation in des moines international airport *Case Studies in Construction Materials* 8 277-291.

[26] Chen X, Chen C, Xu L, Shao Y 2017 Dynamic flexural strength of concrete under high strain rates *Magazine of Concrete Research* 69(3) 109-119.

[27] Qingkun Yu, Liangcai Cai, Jianwu Wang 2018 Experimental and fem research on airport cement concrete direct-thickening double-deck pavement slabs under aircraft single-wheel dynamic loads *Advances in Materials Science and Engineering* 2018 16.

[28] Bieliatynskyi A, Krayushkina E, Skrypchenko A 2016 Modern technologies and materials for cement concrete pavement’s repair, in *Proceedings of the 9th International Scientific Conference Transbaltica* (Elsevier) pp. 344-347.

[29] Shvabyuk V I, Rotko S V, Matkova A V 2016 To the problem of an improved calculation of bending of plates on rigid and elastic foundations *Naukovi Notatki* 54 376-380.

[30] Ho Sang V 1975 *Field Survey and Analysis of Aircraft Distribution on Airport Pavements*. Report FAA RD-74-36, p. 286.

[31] Ying-Haur Lee 1997 Zero-maintenance considerations for concrete pavement design. *Pavements Session of the 13th IRF World Meeting* Toronto, Ontario, Canada, p. 12.

[32] Simon M J 2003 Concrete mixture optimization using statistical methods. Final Report FHWA-RD-03-60 (Gaithersburg: National Institute of Standards and Technology) p. 167.

[33] FAA Airport Pavement Design and Evaluation 2009 AC 150/5320-6E (U.S. Department of Transportation) p. 124.

[34] Roesler J, Evangelista F, Domingues M 2007 Effect of gear positions on airfield rigid pavement critical stress locations, in *materials of FAA worldwide airport technology transfer conference*, Atlantic city, New Jersey, USA, p. 13.

[35] AC No 150/5380-6E 2007 Guidelines and procedures for maintenance of airport pavement. Federal Aviation Administration, Advisory Circular.

[36] Simonyan A M, Arutyunyan A S, Akopyan E A 2014 K voprosu o summirovanii ustalostnykh napryazheniy materialov [On the issue of summation of fatigue stresses of materials] *Izvestiya Natsional’noy akademii nauk Armenii* 67(4) 65-70.

[37] Bin C, Balbo J 2014 Comparing results of airport pavement concrete slab design using damage models of FAARFIELD to MEPDG concrete fatigue model, in *materials of FAA Worldwide Airport Technology Transfer Conference*, Atlantic City, USA.

[38] Davis J 2012 Airport Pavement Design and Evaluation, In *materials FAA Runway Safety and Pavement Maintenance Seminar for Africa*, Retrieved from: http://www.airtech.tc.faa.gov/ATT2014/Papers/P10049%20-%20Bin%20%20&%20Balbo.pdf.

[39] Rodchenko O V 2013 Computer technologies of finite element modeling of airfield rigid pavement, in *Proceedings of the 16th Conference for Junior Researchers “Science – Future of Lithuania”* Vilnius, Lithuania, pp. 65–70.