Analysis of Load Bearing Capacity of Cement Concrete Airfield Pavement's Construction in Relation to its' Changes of Physico-Mechanical Parameters

Mariusz Wesolowski 1, Krzysztof Blacha 1, Pawel Iwanowski 1
1 Airforce Institute of Technology, ul. Ks. Bolesława 6, 01-494 Warsaw, Poland

pawel.iwanowski@itwl.pl

Abstract. An airfield pavement is a designated and properly prepared surface of an airfield functional element (AFE) fulfilling a specific task as part of air operations. A structural system of an airfield pavement is a set of layers, the task of which is to safely take over and transfer loads coming from moving aircraft onto the subsoil. The safety of air operations conducted by aircraft over airfield pavements most of all depends on the load-bearing capacity of their structures. The basic type of airfield pavements includes rigid pavements (elastic) made of cement concrete. The load-bearing capacity state of cement concrete airfield pavements are strongly impacted by concrete properties (physical, mechanical, rheological and resistance to environmental factors), as well as the condition and type of the subsoil directly under the evaluated pavement structure. Adopting an appropriate computational model for the evaluated structure, correct identification of the layers comprising the airfield pavement, accuracy of determining the technical parameters of materials sampled from the structure and a correct assessment of the load-bearing parameter of the subsoil directly under the assessed structure make the load-bearing end result expressed by a PCN index or the permissible number of air operations to be similar to actual conditions. The article presents the dependencies showing the impact of varying physico-mechanical parameters of concrete on the end results of the pavement load-bearing capacity.

1. Introduction
The most frequently encountered and applied structural solution in the functional elements of the onground air traffic in Polish climatic conditions are concrete airfield pavements. Their fundamental and, at the same time, the most important operating parameter is the load-bearing capacity, which explicitly determines the ability of a studied structural system to safely transfer loads from aircraft over a given time.

The condition of concrete airfield pavement load-bearing capacity depends not only on the loads generated by aircraft, but also on numerous external factors, including weather conditions [7]. The load-bearing capacity end result is also significantly impacted by the mechanical properties of concrete used to execute the airfield pavement, as well as the condition and type of subsoil directly under the assessed airfield pavement. As a result, the most important factors impacting the load-bearing capacity of concrete airfield pavements include:

- number of air operations (aircraft loads) taking place or planned on the pavement in question,
- pavement structure cross-section - thickness of individual structural layers,
- concrete flexural strength,
- concrete elasticity modulus,
- Poisson’s ratio of the pavement and substrate structural layers,
- type, compaction and moisture of the subsoil,
- subsoil load-bearing capacity,
- temperature during the conducted field tests.

While the first five parameters can be defined as constant or invariable over a short period of time, it is the subsoil parameters, which can change depending on the current meteorological conditions. The impact of the subsoil on the load-bearing capacity is caused by changing geotechnical parameters, depending on its moisture. In the case of concrete airfield pavements, the impact of the concrete slab deformation phenomenon resulting from temperature effects should also be taken into account. Given the operational safety and reliability of airfield pavements, it is assumed that load-bearing tests shall be conducted in the Spring or late Autumn and should not be executed in the Winter. A comprehensive analysis of a concrete airfield pavement load-bearing capacity state requires the identification of the physical and mechanical materials of its individual structural layers and the subsoil.

2. Elastic deflection measurement

Foreign adopted methods are used to measure the load-bearing capacity of concrete airfield pavements (elastic-rigid structures) in our country. In the case of rigid pavement, the computational model is a slab on a Winkler subsoil, while the subsoil response factor shall be determined during field tests, directly for the soil. The measurements of elastic deflections in airfield pavement structures involves using a heavy impact deflectometer of the HWD (Heavy-Weight Deflectometer) type, which records vertical displacements under the impact of dynamic load resulting from dropping a weight of specific mass on a pressure plate with a diameter of 0.45 m, adhering to the tested pavement. The value of the load generated at the time of the weight drop is 200 kN, while the duration of a single pulse is from 0.025 to 0.03 s. The computational unit pressure on the ground is about 1.25 MPa. A measured deflection basin of the entire structure is used to evaluate the load-bearing capacity of a concrete airfield pavement using an HWD impact deflectometer. The elasticity moduli of individual layers are determined based on the deflection basin and the knowledge of the structural layer thickness and the characteristics of the layer materials. The envelopes of the maximum elastic deflection values measured by all geophones (a number equal to 9) are the result of pavement measurements using an HWD device. This set of values is defined as the deflection basin. Deflection size of the entire basin is a dependency, described by the formula below:

$$ U_i = f(h, E, \nu) $$

where:

- $U_i$ – deflection value of the tested surface at point $i$,
- $f$ – functional relationship of components,
- $h$ – thickness of individual pavement structural layers,
- $E$ – elasticity modulus of individual subsoil and pavement structural layers,
- $\nu$ – Poisson’s ratio of the subsoil and pavement structural layers.

Distribution of deflections in the studied pavements changes along with changing thickness of individual structural layers, their rigidity and the Poisson’s ratio. Subsoil rigidity has the greatest impact on the shape of the entire deflection basin. Variations in the rigidity of a subsoil cause shifting of the entire deflection basin upwards (higher subsoil rigidity) or downwards (lower subsoil rigidity), therefore, they have a significant impact on the values of the deflections at all measurement points. Example values of elastic deflections measured by individual geophones during the HWD measurements on a concrete airfield pavement are shown Figure 2.
The recorded airfield pavement deflection values are used to determine the elasticity moduli of materials in individual layers using an iterative comparison of measured deflections and the theoretical deflections, so that the $F$ function has a minimum value. The relationship below is used for that purpose:

$$F = \sum_{j=1}^{k} (w_j - u_j)^2$$  \hspace{1cm} (2)

where:
- $F$ – approximation function for actual and theoretical values,
- $w_j$ – calculated surface deflections at a distance $r$ from the centre of the loading plate,
- $u_j$ – measured surfaces deflections at a distance $r$ from the centre of the loading plate,
- $k$ – number of geophones (measurement sensors describing the deflection basin) usually equal to 9.

The results can be presented in the form of elastic deflections, deflection moduli and replacement moduli or in the form of pavement load-bearing capacities as per the assumptions of the ACN-PCN method. A concrete slab elastic modulus is determined in a laboratory using cylindrical samples, collected from within the tested pavement.

**3. Subsoil**

A very important factor determining the ability of an airfield pavement structure to accept loads is the load-bearing capacity of the subsoil. It is known that load distributed by a pavement structure acts on a narrower area in the case of a high load-bearing capacity of the subsoil, than in the case of the same structure resting on a low-bearing subsoil. This means a significant restriction (in the first of the said
cases) in the complex impact of adjacent aircraft strut wheels. This is also the principal reason, why the load-bearing capacity was divided into four categories (high, average, low, very low), in order to determine the impact of an aircraft on a pavement using the ACN (Aircraft Classification Number). A subsoil load-bearing category for rigid pavements is determined based on a subsoil response factor k, whereas in the case of elastic pavements, based on the California Bearing Ratio; the CBR. The load-bearing capacity of the subsoil under the concrete airfield pavement structure being assessed shall be determined based on field tests, as per the requirements of the defence standard [3].

4. Mechanical properties
Concrete engineering primarily deals with the properties, which are particularly important from the perspective of its application as a building material. The following concrete property groups are distinguished [1]:
- physical properties,
- mechanical properties,
- rheological properties,
- resistance to environmental impact.

The safety of air operations conducted by aircraft on concrete airfield pavements primarily depends on the aforementioned properties, with the mechanical parameters having the greatest impact. Mechanical properties of concrete include: compressive, tensile, torsional, local pressure, impact, abrasion and dynamic load strength, as well as the elasticity modulus. The parameters, which largely determine the end load-bearing capacity of an assessed cement concrete airfield pavement include: concrete elasticity modulus, concrete flexural strength and Poisson’s ratio.

4.1. Elasticity modulus
The elasticity modulus (Young’s modulus) for concrete is a longitudinal deformability index for concrete and is expressed by a ratio of stress to the corresponding deformation:

$$E = \frac{\sigma}{\varepsilon} \quad (3)$$

where:
- $\sigma$ – strain,
- $\varepsilon$ – deformation.

Bearing in mind that the dependency of $\sigma$ from $\varepsilon$ for concrete is not linearly proportional, strictly defined values $\sigma$ were adopted to determine the elasticity modulus $E$. As a result, the following are, i.a., distinguished:
- initial modulus $E_0$,
- standard modulus $E_b = E$,
- instantaneous modulus $E_{\varepsilon}$,
- dynamic modulus $E_{\text{dyn}}$.

The differences involve adopting the values of stresses, for which the elasticity modulus $E$ is determined, which is shown in figure 3 [1].

The graph indicates that an elastic modulus for a given $\sigma$ is equal to the tan of the angle formed by the tangent of the curve $\sigma$-$\varepsilon$ with the horizontal axis of the graph. The computational module for any $\sigma$ is an instantaneous module, whereas the base in structural calculations is the standard module $E_b$ determined for the secant between $\sigma_1 = 0.1 \cdot f_c$ and $\sigma_2 = 0.3 \cdot f_c$, which are reflected by the deformations $\varepsilon_1$ and $\varepsilon_2$. 

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Figure 3. Interpretation of the concrete elastic modulus $E$

The elasticity modulus of concrete increases along with its compressive strength, since it is directly dependent on the elasticity modulus of the aggregate used and its quantity per volume unit. The literature of the subject includes formulas describing the elasticity modulus of concrete, even without the need to conduct appropriate tests, e.g. acc. to Graf [1]:

$$E_\text{c} = \frac{100000}{0.17 + \frac{30}{f_c}}$$  \hspace{1cm} (4)

where: $f_c$ – standard compressive strength of concrete.

The actual values of the elasticity moduli of concrete used for airfield pavements shall be determined experimentally in laboratory conditions on samples collected directly from the structure of the pavement being assessed.

4.2. Flexural strength and Poisson’s ratio

In research practice, the load-bearing capacity of concrete airfield pavements is determined during field tests, which involve measuring the thickness of individual structural layers of the pavement and determining the flexural strength of the surface layer. The type of individual structural layers of the pavement and their thicknesses are determined based on $\Phi 150$ mm boreholes in the tested pavement. The boreholes shall be conducted according to [5]. The flexural strength is tested on cylindrical samples from the pavement, as per [2]. The flexural strength shall be determined as follows determine the tensile strength when splitting the core boreholes $\Phi 150$ mm, as per [10] and convert the splitting tensile strength of cement concrete to the tensile strength, according to the formula:

$$f_{xz} = f_{ct} \times 1.5$$  \hspace{1cm} (5)

where:

$f_{ct}$ – splitting tensile strength of cement concrete determined according to the Brazilian method,

$f_{xz}$ – flexural strength of cement concrete.

In the case of cement concrete airfield pavements, the conversion factors applied when converting the tensile strength of concrete when splitting a cylinder to concrete flexural strength is, according to [2], 1.5.

Depending on the type and properties of the used aggregate, the Poisson’s ratio of concrete usually ranges from 0.15 to 0.22. In practice, to calculate the load-bearing capacity of concrete airfield pavements for concrete used to execute the surface layer, the adopted Poisson’s ratio is equal to 0.16.
5. Impact of mechanical parameters on pavement load-bearing capacity

5.1. Theoretical analysis

The load-bearing capacity of airfield pavements can be expressed by the PCN ratio or the permissible number of air operations. In both cases, the number of permissible load repetitions \( N \) is significant, directly impacting the load-bearing capacity value. It should be noted that the number of load repetitions \( N \) is a limited number.

The number of permissible repetitions is calculated depending on the adopted computational model for the airfield pavement structure being assessed. In the case of rigid pavements, made of cement concrete, the following formula resulting from the criterion of permissible stresses is used [9]:

\[
N = \left[ \frac{f_{sz}}{\sigma} \times \left( \frac{E}{30000} \right)^{1.3} \right]^{(1/0.233)} \times 10^4
\]  

(6)

where:
\( N \) – number of permissible load repetitions,
\( f_{sz} \) – flexural strength of concrete [MPa],
\( \sigma \) – tensile stresses at bending, determined in the bottom part of the concrete slab [MPa],
\( E \) – elasticity modulus of concrete [MPa].

Based on many years of researching the load-bearing capacities of airfield pavements conducted by the Department of Airfields at the Air Force Institute of Technology, relationships were developed, which showed the impact of varying mechanical parameters of concrete on the load-bearing end results for the pavements being assessed, shown in clause 4.3. The results of the conducted theoretical analysis are shown in tables 1-2 below.

Table 1. Dependence of the permissible number of air operation on the mechanical properties of concrete (at \( k=25 \) MN/m³)

| Concrete property | Concrete slab thickness \( h=0.25 \) m | Category D subsoil, \( k=25 \) MN/m³ |
|------------------|--------------------------------------|----------------------------------|
|                  | \( E \) [MPa]                        | \( f_{sz} \) [MPa]               | Permissible number of air operations |
| \( E \) [MPa]    | 25 000 | 30 000 | 35 000 | 25 000 | 25 000 | 30 000 | 30 000 | 35 000 | 35 000 |
| \( f_{sz} \) [MPa] | 4.5 | 4.5 | 4.5 | 5.0 | 5.5 | 5.0 | 5.5 | 5.0 | 5.5 |
| Permissible number of air operations | 9 900 | 24 900 | 54 900 | 15 500 | 23 400 | 39 100 | 58 800 | 86 200 | 129 800 |
|                  | \( E \) [MPa]                        | \( f_{sz} \) [MPa]               | Permissible number of air operations |
| \( E \) [MPa]    | 25 000 | 30 000 | 35 000 | 25 000 | 25 000 | 30 000 | 30 000 | 35 000 | 35 000 |
| \( f_{sz} \) [MPa] | 4.5 | 4.5 | 4.5 | 5.0 | 5.5 | 5.0 | 5.5 | 5.0 | 5.5 |
| Permissible number of air operations | 35 800 | 91 100 | 200 800 | 56 200 | 84 600 | 143 100 | 215 400 | 315 500 | 475 000 |
|                  | \( E \) [MPa]                        | \( f_{sz} \) [MPa]               | Permissible number of air operations |
| \( E \) [MPa]    | 25 000 | 30 000 | 35 000 | 25 000 | 25 000 | 30 000 | 30 000 | 35 000 | 35 000 |
| \( f_{sz} \) [MPa] | 4.5 | 4.5 | 4.5 | 5.0 | 5.5 | 5.0 | 5.5 | 5.0 | 5.5 |
| Permissible number of air operations | 109 700 | 281 100 | 616 200 | 172 400 | 259 600 | 441 800 | 665 100 | 968 500 | 1 457 900 |
Table 2. Dependence of the permissible number of air operation on the mechanical properties of concrete (at k=90 MN/m³)

| Concrete property | Category B subsoil, k=90 MN/m³ | Concrete slab thickness h=0.25 m | E [MPa] | f_{zc} [MPa] | Permissible number of air operations |
|-------------------|---------------------------------|----------------------------------|--------|-------------|-----------------------------------|
|                   |                                 |                                  | 25 000 | 4.5         | 19 900                            |
|                   |                                 |                                  | 30 000 | 4.5         | 49 100                            |
|                   |                                 |                                  | 35 000 | 4.5         | 107 100                           |
|                   |                                 |                                  | 25 000 | 5.0         | 47 000                            |
|                   |                                 |                                  | 25 000 | 5.5         | 77 100                            |
|                   |                                 |                                  | 30 000 | 5.0         | 116 100                           |
|                   |                                 |                                  | 30 000 | 5.5         | 168 300                           |
|                   |                                 |                                  | 35 000 | 5.0         | 253 300                           |

|                   |                                 |                                  | 25 000 | 5.5         | 253 300                           |
|                   |                                 |                                  | 30 000 | 5.5         | 77 100                            |
|                   |                                 |                                  | 30 000 | 5.5         | 116 100                           |
|                   |                                 |                                  | 35 000 | 5.5         | 168 300                           |
|                   |                                 |                                  | 35 000 | 5.5         | 253 300                           |

|                   |                                 |                                  | 25 000 | 5.5         | 253 300                           |
|                   |                                 |                                  | 30 000 | 5.5         | 77 100                            |
|                   |                                 |                                  | 30 000 | 5.5         | 116 100                           |
|                   |                                 |                                  | 35 000 | 5.5         | 168 300                           |
|                   |                                 |                                  | 35 000 | 5.5         | 253 300                           |

|                   |                                 |                                  | 25 000 | 5.5         | 253 300                           |
|                   |                                 |                                  | 30 000 | 5.5         | 77 100                            |
|                   |                                 |                                  | 30 000 | 5.5         | 116 100                           |
|                   |                                 |                                  | 35 000 | 5.5         | 168 300                           |
|                   |                                 |                                  | 35 000 | 5.5         | 253 300                           |

5.2. Numerical analysis

The following assumptions were adopted in order to conduct a numerical analysis using the finite element method (FEM):
- code C design aircraft - Boeing 737 800,
- maximum take-off weight 79 242 kg (load generated by a single wheel of the main strut – 260 kN),
- aircraft tyre pressure - 1.41 MPa,
- concrete surface layer thickness - 0.30 m,
- concrete elasticity modulus - 30 000 MPa,
- concrete flexural strength 5.5 MPa,
- Poisson’s ratio 0.16,
- concrete class C 35/45,
- subsoil category (A - k=120 MN/m³, B - k=90 MN/m³, C - k=50 MN/m³, D - k=25 MN/m³)

The numerical analysis was conducted using the Autodesk® Robot™ Structural Analysis Professional software. The obtained results of the FEM numerical simulation under the aforementioned assumptions are shown in figure 4, in the form of a elastic deflection distribution for a concrete slab on a load-bearing category D subsoil.

Whereas table 3 shows the maximum deflection values for individual load-bearing categories of the subsoil, obtained during the numerical analysis.

Table 3. Maximum values of elastic deflections

| Subsoil load-bearing category / k [MN/m³] | A / 120 | B / 90 | C / 50 | D / 25 |
|------------------------------------------|---------|--------|--------|--------|
| Max. deflection value [cm]              | 0.056   | 0.071  | 0.115  | 0.196  |
Figure 4. Distribution of deflections in a pavement structure resulting from applied load equal to 260 kN

5.3. Statistical analysis

The statistical analysis was conducted using the Statistica PL software package. Figure 5 below show the relationships depicting the impact of concrete mechanical parameter variations and the subsoil load-bearing category on the load-bearing capacity end result for concrete airfield pavements, expressed as the permissible number of air operations. The article presents the results of an analysis conducted under the assumptions of a constant slab thickness equal to 0.30 m. Whereas the parameters modified for the purposes of the analysis were: subsoil load-bearing capacity, concrete elastic modulus and concrete flexural strength. It should be emphasized that all of the adopted parameters are commonly used in the design solutions regarding concrete airfield pavements in domestic conditions.

Figure 5. Dependence of the number of permissible air operations on the concrete elasticity modulus and concrete flexural strength (for subsoil load-bearing category B and D)

Figure 6 show the waveform of load-bearing capacity result variations depending on the subsoil category, concrete elasticity modulus, concrete flexural strength, under the assumption of a constant plate thickness \( h = 0.30 \) m.
Figure 6. Impact of the subsoil load-bearing category and concrete flexural strength on the load-bearing state (under the assumption of a constant plate thickness $h=0.30$ m and elasticity modulus $E=25,000$ MPa (left) and $E=35,000$ MPa (right))

6. Conclusions
The condition of the load-bearing capacity of cement concrete airfield pavements is impacted by numerous factors. The end result, expressed by a PCN index or the permissible number of air operations, depends not only on the loads generated by aircraft and the weather conditions, but also on the mechanical properties of the concrete used to execute the airfield pavement, as well as the condition and type of the subsoil directly under the pavement structure being evaluated. The article discusses the impact of the most important mechanical properties of concrete, i.e., elasticity modulus, flexural strength and the Poisson’s ratio, as well as the load-bearing parameters of the subsoil on the load-bearing capacity of airfield pavements.

All of the aforementioned parameters were used to conduct thorough theoretical, numerical and statistical analyses aimed at showing their direct impact on the final load-bearing value expressed by the permissible number of air operations. The obtained results and developed relationships are shown in clause 4 of the article. They can be used as a base to conclude that together with increasing: concrete elasticity modulus, its flexural strength, thickness of the surface layer and an appropriately higher subsoil load-bearing category, the load-bearing capacity of the airfield pavement being assessed increases. It is particularly important from the economic aspect of designing airfield pavements in the cement concrete technology. It should be emphasized that every centimetre of the analytically calculated concrete airfield pavement thickness directly depends on the adopted assumptions in terms of the load-bearing capacity, namely, on the type of the design aircraft, i.e., the quantity of the load generated by it and its ACN, concrete class, its elasticity modulus, flexural strength and the Poisson’s ratio, the soil-water conditions determined by the subsoil load-bearing category and the period of assumed operation of the pavement in question. Therefore, it can be concluded that it would be justified for further research work to include conducting such an analysis that would present the impact of each consecutive centimetre of a concrete airfield pavement on its load-bearing capacity.
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