ASSESSMENT OF LOAD CAPACITY OF THE AIRPORT PAVEMENT STRUCTURE WITH THE USE OF THE ACN-PCN METHOD

The structures of the airport pavements are designed for defined operational time, assuming the predicted intensity and structure of the air traffic. The safety of air operations conducted by aircrafts on airport pavements depends mostly on their load capacity and design. Therefore, the load capacity inspections should be performed periodically, as the information about the current operational condition of the airport pavement is the basis for decisions on types of aircrafts allowed for traffic, as well as traffic intensity and dates of renovation or modernization works.

Currently, the load capacity of airport pavements is assessed with the use of the ACN-PCN method, implemented by the ICAO (International Civil Aviation Organization). This article presents the method of determination and description of the PCN index.

Keywords: airport pavements, pavement designs, calculation models, PCN load capacity index.

1. Introduction

The structure of the airport pavement is usually formed by groups of layers designed for taking and transferring loads from moving aircrafts and helicopters to the ground subsoil in a way which assures its specified durability. One of the basic operational properties of the airport pavement is its load capacity. The load capacity means the ability of the structure to transfer the loads from the aircrafts in a specified time. The load capacity of the pavement depends not only on the aircraft loads but also on many external factors, including the weather conditions [2, 8, 12].
In case of pavements made of cement concrete, the following parameters may be listed as most important:
- number of air operations realized or planned on the pavement,
- concrete bending tensile strength,
- cross-section of the pavement structure,
- type, density, and humidity of the ground subsoil,
- temperature during the tests.

The first three parameters may be defined as constant or invariable in a short time period, while the parameters of the ground subsoil may change depending on the current weather conditions. In case of airport pavements made of cement concrete, it is also required to take into consideration the phenomena of deformation of concrete slabs due to temperature. The influence of the ground subsoil on the pavement load capacity is caused by changes of the soil geotechnical parameters depending on its humidity.

Taking into consideration the pavement operation safety standards, it is usually assumed that the load capacity tests should be performed during spring or late autumn, not during winter. The information about the operational condition of the pavement is the basis for decisions on the types of aircrafts allowed for traffic, as well as traffic intensity and dates of renovation or modernization works of the airport pavement. The complete analysis of the load capacity of the airport pavement requires the identification of the physical and mechanical parameters of materials in the individual structural layers and of the ground subsoil. The identification should include actual operational conditions of the pavement. Taking into consideration the assessment of the operational condition of the airport pavements, it is necessary to perform the periodical load capacity tests.

2. Airport pavement structures

The employees of the Airport Department at the Air Force Institute of Technology throughout a few years have gained experience in load capacity tests of airport pavements in military objects and in civil airports, which confirmed that there are three basic types of a pavement structure in Poland:
- rigid (elastic) pavements of cement concrete,
- flexible pavements of asphalt concrete,
- complex (elastic – flexible) pavements in which the rigid structure is reinforced with a layer of asphalt concrete.
The correct identification of the structure has a significant influence on the determination of the load capacity of airport pavements. It results from the fact that the method of transferring the loads from the aircrafts to the ground subsoil depends on the type of airport pavement. Depending on its type and the operation method, appropriate mathematical models, presented below, are used for expressing the character of influence of the aircraft on the pavement.

3. ACN-PCN method of assessment of load capacity of airport pavements

The ACN-PCN method for assessing the load capacity of airport pavements has been implemented by the ICAO (International Civil Aviation Organization) in 1983 [5]. In this method, the ACN (Aircraft Classification Number) expresses the relative influence of the aircraft on the airport pavement when the standard load capacity of the ground subsoil is determined. The ACN is determined according to the procedure defined by the ICAO, assuming that the standard quantities in the calculation process are:

- pressure in a single wheel tyre of 1.25 MPa,
- allowable bending stress in a concrete slab (for rigid pavements) of 2.75 MPa,
- allowable number of loads in case of flexible pavements,
- load capacity of the ground subsoil, described with the subsoil reaction coefficient $k$ for rigid pavements and with CBR index for flexible pavements.

The ACN is expressed with the following formula:

$$ ACN = 2 \cdot P_r $$

where: $P_r$ – equivalent load in thousands of kilograms of such value that the pavement thickness required for its transferring is equal to the thickness determined as for the actual load:

$$ P_r = \pi \cdot q \cdot a^2 $$

where: $q$ – uniform load of intensity of 1.25 MPa distributed on a circular area of radius $a$.

The load capacity of airport pavements depends on many factors. In case of a rigid pavement, those are: the shape and dimensions of concrete slabs, their
adherence to the ground subsoil and concrete strength parameters. The load capacity of a flexible structure depends on the number and thickness of layers and the physical and mechanical properties of the materials of those layers. The following have a particularly significant influence: the rigidity modulus of the individual structural layers, the corresponding values of Poisson coefficient, the condition of the inter-layer connections, cracks in the pavement layers, water penetrating the structure and the ground subsoil, and the temperature of the asphalt layers.

An important factor deciding on the ability of the pavement to take the loads is the load capacity of the ground subsoil. It is known that the load distributed by the pavement structure acts on a narrower area in case of high subsoil load capacity than when the same structure is supported on a subsoil of low load capacity. It causes a significant limitation (in the first of the mentioned cases) of the complex influence of the adjacent wheels of the aeroplane legs. Consequently, in order to determine the aeroplane influence on a pavement through the ACN, the discussed method divides the subsoil load capacity into four categories: high, medium, low, and very low. Table 1 presents the ranges of the subsoil load capacity characteristic for those categories and assumed standard values, diversifying the physical quantities describing that parameter according to the pavement type. ACN numbers for the aeroplane are determined taking into consideration the standard values of the ground subsoil load capacity.

**Table 1**

Ranges of load capacity for the airport pavements

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<td>$&gt;13$</td>
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<td>Medium load capacity</td>
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<td>Low load capacity</td>
<td>$25-60$</td>
<td>$4-8$</td>
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<td>Very low load capacity</td>
<td>$&lt;25$</td>
<td>$&lt;4$</td>
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For each aircraft the ACN number is the set of numbers depending on the type of the airport pavement structure (rigid and flexible) and the ground subsoil load capacity. The tables including the values of ACN for the most common aircrafts are presented in [9].

The PCN (Pavement Classification Number) expresses the load capacity of an airport pavement for a limited number of flights of aircrafts with the ACN = PCN. It corresponds to a 1/500 of the allowable load (expressed in kilograms of weight) applied to the pavement through a single wheel with standard pressure of 1.25 MPa.

In many countries during the assessment of the load capacity of the airport pavement structure, procedures opposite to dimensioning (back calculation) are used [1, 5]. There are two groups of methods used in practice of designing the thicknesses of structural layers of airport pavements: empirical and theoretical-empirical. The essence of theoretical-empirical methods consists in assuming a calculation model, analysing its strength and comparing the calculated stresses of strains with the allowable values. This algorithm is used by such methods as the Shell method as well as the Czechoslovak, FAA, Belgian, and Russian methods. The empirical methods specify formulas or charts for direct calculation of thickness of layers and are valid for the conditions in which they have been verified. The most common ones include the FAA (Federal Aviation Administration) [1], Canadian, and French [5] methods.

The group of empirical methods uses the CBR reverse dimensioning procedure, which is practiced in USA, France, Canada [1, 5]. The structure thickness recalculated for breakstone is calculated from the empirical relationship:

\[ h = t_\alpha \sqrt{\frac{P}{8.1 \cdot CBR}} - \frac{A}{\pi} \]  

where:
- \( h \) – equivalent pavement structure thickness in breakstone (in inches),
- \( P \) – equivalent single-wheel load (in lbs),
- \( CBR \) – subsoil load capacity (in %),
- \( A \) – contact area between wheel and pavement (in square inches),
- \( t_\alpha \) – coefficient depending on the repeatability of loads and number of wheels in the leg, having various values for various types of aircrafts.

In this method the identification includes the thicknesses of the layers which are recalculated to the breakstone, and the subsoil load capacity factor \( CBR \) determined upon the basis of the soil samples from under the pavement structure. Having those parameters, the formula (2) is used to determine the value of the
allowable load and then the type of the operated aeroplane and its ACN number. It is assumed that the pavement load capacity factor PCN equals to the ACN. In this method, there are specified the relationships between the subsoil load capacity and the thickness of layers recalculated to the breakstone. In calculating the load capacity of the airport pavement, the procedure algorithm is similar to the CBR method.

For dimensioning the airport pavements made of cement concrete, the Westergaard model is used, i.e. the plate placed on the subsoil of a Winkler type described by the subsoil reaction coefficient $k$ [5]. In this model, the identification includes the modulus of elasticity of a concrete slab and the reaction coefficient of the subsoil which is determined during direct measurement on the ground. The plate of diameter of 0.76 m is loaded with such force that its displacement of 1.25 mm is obtained. The ratio of the measured force to the displacement is the subsoil reaction coefficient. This method is used, among others, in USA, France, and Canada [1, 5]. The modulus of elasticity of a concrete slab is determined in the laboratory with the use of cylindrical samples taken from the structure of the tested pavement. The load capacity is calculated by determining the allowable load applied to the pavement which does not cause pavement destruction in the assumed time, i.e. for a specified number of repetitions. The type of operated aircraft is determined for the allowable load. The PCN load capacity indices for the pavement are determined by comparison with ACN indices for an aeroplane allowed for operation.

In Poland, the methods adopted from other counties are used for testing the airport pavement load capacity [5]. In the case of flexible pavements, the calculation model is the equivalent elastic system of the double-layer half-space. The moduli for the subsoil are recommended to be determined through the tests with the use of measurement plates directly on the ground, and the moduli of layers are determined in laboratory tests. For rigid pavements, the model is the plate on the Winkler subsoil, and the reaction coefficient is recommended to be determined in direct tests on the ground. Currently, in order to assess the load capacity of airport pavements designed for lighter types of aircrafts, the light deflectometer of FWD (Falling Weight Deflectometer) type is used, while for pavements designed for heavier types of aircrafts, the heavy impact deflectometer of HWD (Heavy Weight Deflectometer) type is used. The principle of operation for HWD and FWD devices is the same, but for HWD two press plates may be used, one of diameter of 0.3 m and the second of 0.45 m. The elastic deflections of the airport pavement are measured under the influence of the dynamic load on the basis of dropping the weight of defined value on the pressing plate adhering to the tested pavement. During the drop the generated load value varies from 30 to 240 kN.
depending on the pavement structure type, and the time of one impulse ranges from 0.025 to 0.03 s. The conversion elementary pressure on the subsoil is then approximately 1.25 MPa. During the measurement nine geophones installed on the measurement strip and centrally under the loading plate record the deflections of the tested pavement. The maximum distance from the measurement point to the centre of the loading plate is 2.5 m. The device operation is completely automatic. For assessing the load capacity of the airport pavement with use of impact deflectometer of HWD type, the measured deflection bowl of the tested structure surface is used. Upon the basis of the deflection bowl and knowledge of thickness of the structural layers as well as the characteristics of materials they are made of, the moduli of elasticity of individual layers are determined. The result of measurements of the pavement with use of an HWD device are the envelopes of the maximum values of elastic deflections measured by all geophones. That set of values is defined as the deflection bowl and is presented in Fig. 1 [2].

Fig. 1. View of deflection bowl from the measurements with an HWD device

The quantity of deflections in the whole bowl is the relationship described by the following formula [2]:

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

where:

- $U_i$ – deflection value for tested surface in $i$ point,
- $f$ – function relationship of the components,
- $h$ – thickness of the individual structural layers of the pavement,
- $E$ – modulus of elasticity of the individual structural layers of the pavement and subsoil,
- $\nu$ – Poisson coefficient of the structural layers of the pavement and subsoil.
When the thickness, the rigidity and the Poisson coefficient of individual layers change, the distribution of deflections changes as well. The rigidity of the subsoil has the biggest influence on the form of the whole deflection bowl. Changes of rigidity of the ground subsoil significantly influence the values of deflections in all measurement points. They cause displacement of the whole deflection bowl, either up (higher subsoil rigidity) or down (lower subsoil rigidity). But the changes of rigidity of the upper structural layers of the pavement and substructure change the bowl form only in a specified distance from the centre of applied load. Changes of rigidity of the upper pavement layers reveal a tendency similar to the change of rigidity of that layer. The influence of the Poisson coefficient on the quantity and form of the deflection bowl was the subject of many analyses [2]. The value of the coefficient depending on the material type in the layer may range from 0.2 to 0.5. The diversification of that parameter in the pavement structure leads to analogical results as found for changing the rigidity and thickness of layers. Moreover, the conclusions concerning the influence of the Poisson coefficient on defects of the tested surface result directly from the solution of the problem formulated for the half-space. In the half-space, the deflections are proportional to the known formula in a form (4) which shows that the Poisson coefficient has low influence on the deflection values [2].

\[
u = \frac{2 \cdot (1 - \nu^2) \cdot p \cdot r_0 \cdot u_z(r, z)}{E}
\]

where: \( u \) – deflection on the surface,

\( \nu \) – Poisson coefficient,

\( p \) – contact pressure,

\( r_0 \) – radius of the contact area,

\( E \) – modulus of elasticity,

\( u_z(r, z) \) – function depending on the spatial coordinates only.

Upon the basis of recorded deflection values of the airport pavement, the moduli of elasticity of material of individual layers are determined with the use of iterative comparing of measured deflections and theoretical deflections in such a way that the function \( F \) has the minimum value. To do this, the following relationship is used:

\[
F = \sum_{j=1}^{k} (w_j - u_j)^2
\]
where: $F$ – function of approximation of the actual and theoretical values,

$w_j$ – calculated pavement deflections in the distance $r$ from the loading plate centre,

$w_j$ – measured pavement deflections in the distance $r$ from the loading plate centre,

$k$ – number of geophones (measurement sensors describing the deflection bowl), usually 9.

The results may be presented in form of deflections, moduli of deformation, substitute moduli, or pavement load capacity according to the assumptions of the ACN-PCN method. The surface moduli, depending on the distance between the geophones and the centre of the loading plate, are determined from the following formulas:

$$E_0(0) = \frac{2 \cdot (1 - \nu^2) \cdot q \cdot a}{u(0)}$$  \hspace{1cm} (6)

$$E_0(r) = \frac{\left(1 - \nu^2\right) \cdot q \cdot a^2}{r \cdot u(r)}$$  \hspace{1cm} (7)

where:

$E_0(0)$ – surface modulus under the loading plate,

$E_0(r)$ – surface modulus in the distance $r$ from the loading plate centre,

$E_Z$ – substitute modulus of the tested surface,

$a$ – plate radius,

$\nu$ – Poisson coefficient,

$u$ – deflection in tested point (0 – under the loading plate),

$q$ – stress under the loading plate.

For the estimation of the substitute modulus of the tested airport pavement structure, the shortened version of the above formulas is used:

$$E_Z = \frac{2 \cdot q \cdot a}{u(0)}$$  \hspace{1cm} (8)

Fig. 2 presents the HWD device used by AFIT for measurements of the elastic deflections of airport pavements.
In the ACN-PCN method, the complete information of the load capacity of the airport pavement should include the following data:

- PCN,
- type of pavement structure,
- category of subsoil load capacity,
- category of pressure in the tyres,
- used assessment method.

4. Calculation models of the airport pavement structures

The basic problem in dimensioning airport pavements is assuming a calculation model for the structure describing the mechanical properties of individual layers. It is very important that the used model characterizing by the given parameters acts under the operating load in a way possibly consistent with the behaviour of the actual layers which it describes. With the development of new technologies and computer techniques, in the last decades we have been able to observe a continuous evolution of the airport pavement structure models in the methods of dimensioning pavements. More and more often we find use for models more complicated in their notation but also more approximated to the real structure behaviour.

Depending on the type of the airport pavement structure and its operation method, the following mathematical models are used in order to describe the character of the influence of the aircraft on the pavement:

- model of plate of finite dimensions in plane, placed on a substrate of a Winkler type – for a rigid pavement,
- model of elastic layered half-space – for a flexible pavement.
The solution of the model of a plate with finite dimensions in plane has been developed by Westergaard [13]. The plate in that model has been described by the Young’s modulus $E$, Poisson coefficient $\nu$, and thickness $h$, and the subsoil has been described by the subsoil reaction coefficient $k$. The solution of the model of the layered half-space has been developed by Burmister, Kogan, Nowotny, Hanušek, and others. In that model, the layers and the subsoil are described by the moduli of elasticity $E_i$, Poisson coefficient $\nu_i$, and thicknesses $h_i$. For the elastic half-space loaded on the surface (flexible pavement), the Boussinesque's solution is known. For the pavement of a complex structure, it requires to perform an analysis and determine which element of the structure is dominating; complex pavements should be classified as either rigid or flexible pavements. In doubtful cases they are classified as flexible.

### 4.1. Model of an airport pavement on a Winkler type substrate

The airport pavement with a rigid structure, i.e. in form of plates of finite dimensions in plane placed on an inertialess substrate of a Winkler type is described by the Westergaard model, used most often in the global airport technique. Westergaard, who published his theory of designing pavements made of cement concrete for the first time in 1927, has contemplated the possibility of “quarter-infinite” plates, taking into consideration the three most characteristic locations of the load which models the wheel pressure, i.e. in the corner, in the centre, and on the edge of the plate. Those load cases are shown in Fig. 3.

![Plate calculation schemes according to the Westergaard model](image)

The derived formulas describing the state of the maximum stress in the plate for mentioned load cases have the following form [6, 7, 10]:

- for location I:
\[ \sigma_r = \frac{3P}{h^2} \left[ 1 - \left( \frac{a \sqrt{2}}{1} \right)^{0.6} \right] \]  

(9)

– for location II:

\[ \sigma_r = 0.275 \frac{P}{h^2}(1-\nu) \left[ 4\log \left( \frac{1}{b} \right) + 1.069 \right] \]  

(10)

– for location III:

\[ \sigma_r = 0.529(1+0.540\nu) \frac{P}{h^2} \left[ 4\log \left( \frac{1}{b} \right) + 0.359 \right] \]  

(11)

where: \( P \) – plate load [kN],
\( h \) – plate thickness [m],
\( \nu \) – Poisson coefficient,
\( l \) – radius of relative plate rigidity: 
\[ l = 4 \sqrt{\frac{E \cdot h^3}{12 \cdot (1-\nu^2) \cdot k}} \]
\( E \) – modulus of plate elasticity [MPa],
\( k \) – substrate reaction coefficient [MPa/m],
\( a \) – radius of tyre contact with pavement [m],
\( b \) – equivalent radius taking into consideration the load distribution in the lower plate part [m],

\[ b = \sqrt{1.6a^2 + h^2} - 0.675h, \text{ when } a < 1.724h, \quad b = a, \text{ when } a > 1.724h. \]

Westergaard has also specified the relationships for calculating the temperature stress. The Westergaard model is used in such dimensioning methods as the PCA method (Portland Cement Association), the older version of FAA method (Federal Aviation Administration), the French method, the Czechoslovak method, and the British method (LCN-LCG). His formulas have also found use in the OSŻD method (Organizacja Sotrudniczestwa Żelaznych Dorog – Rail Cooperation Organization). It is also required to note that using the Westergaard model is limited in the situation when the plate is placed on the layered system, e.g. on an old pavement. Then there is a problem of estimating the value of the substrate reaction coefficient \( k \). Moreover, the model of a Winkler type substrate does not
allow for calculation of stress and strain in the substrate. Most criteria applying to
the substrate are connected with the modulus of elasticity and the value of acting
vertical stress.

4.2. Model of the airport pavement on a layered elastic half-space

In the model of the airport pavement on a layered elastic half-space, each
layer has the infinite dimension in the horizontal plane and is characterized by
thickness $h_i$, modulus of elasticity $E_i$, and Poisson coefficient $\nu_i$. Those layers are
placed on the elastic half-space (substrate) which is described by the modulus of
elasticity $E_1$ and Poisson coefficient $\nu_1$, and has unlimited dimension in the hori-
zontal and vertical planes, i.e. $h_1 = \infty$. That model is shown in details in Fig. 4.

![Fig. 4. Model of elastic layered half-space](image)

The model in the form of an elastic layered half-space is one of the pavement
models most adequate to reality and is used in the airport technique more and
more often. It is used, among others, in the following methods of dimensioning
and designing the reinforcements: the FAA, the Shell, and the Czechoslovak
method. That model is also used by Szydło, Pilujski, Pownug [7, 11] in identifying
airport pavements with the static method.

The discussed models are used for describing the static phenomena. Devel-
opment of new methods in identifying the pavement load capacity as well as im-
pact and harmonic tests was an inspiration for creating the dynamic models. Such
attempts have been made e.g. by Borkowski et al. [3]. In the previous practice,
the influence of wave phenomena on the durability of the pavement structure has
been usually omitted. It resulted from underestimating that influence and from
calculation problems [4]. In the actual layered systems there are complex dynam-
ic phenomena, among which the occurrence of various types of waves may be
distinguished: transverse waves, longitudinal waves, Rayleigh surface waves and Love waves [10]. Those waves, after reaching the boundary of layers of different physical properties, are refracted and reflected, which leads to creation of new disturbances. Therefore, the described situation makes it necessary to select the intermediate path, consisting in finding the relationship between the dynamic and the static tests results, upon the basis of which it will be possible to identify the system parameters using one of the described inertialess models.

5. Presentation of load capacity results

In accordance with the assumed arrangements in the ACN-PCN method, the load capacity of the airport pavement is described by a group of symbols presenting the individual parameters of the structure and informing of the PCN calculation method, e.g. PCN 48/R/B/X/T. The exemplary notation indicates a rigid pavement (R) on a ground subsoil of medium load capacity (B) with the surface layer able to take the pressure up to 1.5 MPa (X). The PCN index has been determined with the use of a technical method (T) using the impact deflectometer. Therefore, such airport pavement may be used without limitations by aircrafts with the ACN not higher than the exemplary PCN of 48. For instance, the ACN for the aeroplane of Airbus A320-200 class is 46; therefore, it may safely take off and land on the airport pavement presented in the example. A detailed method of interpretation of the above notation is shown in Table 2.

Table 2

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Checking if a given aeroplane may safely operate on a given airport consists therefore in comparing the PCN of the pavement for individual functional elements of the airport with the ACN of the aeroplane. It is also required to note that the ICAO has introduced in Annex 14, appendix A, section 19 [4] limitations in traffic of aeroplanes exceeding the load capacity (causing the overload) of a given pavement when ACN>PCN:

- for rigid or complex pavements in which the rigid layer is the main structural element – the limited (occasional) traffic is allowed when the ACN>PCN relationship is exceeded by no more than 5%,
- for flexible pavements – the limited (occasional) traffic is allowed when the ACN>PCN relationship is exceeded by no more than 5%,
- the annual number of overloads should not exceed 5% of the total annual number of operations on a given functional element of the pavement.

6. Summary and conclusions

The load capacity is one of the most important parameters influencing the assessment of the technical condition of airport pavement structures. The assessment method presented in the article (ACN-PCN) is non-destructive, dynamic, and very efficient. It also allows for classification of the pavement load capacity upon the basis of rheological tests results for layer materials and, therefore, for precise forecasting of the operational time of a pavement with known prediction of the land traffic of the aircrafts.

In Poland, it is assumed that airport pavements of flexible structure are designed for a 20-year period of operation, while pavements of rigid structure for 30 years. The international methods of designing airport pavements taking into consideration the above operation periods assume three categories of air traffic intensity for which the nominal numbers of air operations are specified [14]:

- low – 10,000 air operations,
- medium – 100,000 air operations,
- high – 250,000 air operations.

In accordance with the assumptions of the ACN-PCN method, the load capacity of airport pavements is expressed by the PCN index, whose method of determination is presented in this article.
References