STRUCTURAL EVALUATION AND ESTABLISHING PCN VALUES BASED ON NON-DESTRUCTIVE TESTING, CASE STUDY-JORGE CHAVEZ INTERNATIONAL AIRPORT, LIMA, PERU

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ABSTRACT

Pavement condition evaluation of airport runways, taxiways and apron areas is an important aspect of operating safer and efficient air transport system for any country. Non-destructive testing (NDT) of airfield pavement has gained popularity in the past few decades due to an increase of aircraft traffic on major airports where airport operators cannot afford to close the airside pavement areas for time consuming pavement evaluation activities. Non-destructive deflection testing takes only a few minutes to complete the testing at a location and the equipment can be moved away from active airside areas very quickly. Further, the accuracy and reliability of the NDT equipments realized by the pavement community has also increased its popularity. Lima Airport Partners contracted the consultant to conduct a non-destructive deflection testing study at the Jorge Chavez International Airport in Lima, Peru. The objective of this study was to determine the structural condition of different pavement areas of the airport and establish a Pavement Classification Number (PCN) for each pavement area. Non-destructive deflection tests were performed using a Heavy Weight Deflectometer and analysis was performed using a specialized software. This software can back-calculate pavement layer moduli based on non-destructive deflection test data and determine the remaining life of the pavement structure based on estimated aircraft traffic. It can also determine a PCN value at each NDT test point based on International Civil Aviation Organization (ICAO) guidelines. This paper describes methodology of using non-destructive testing for structural condition evaluation and establishing PCN values for different pavement areas of the airport.

KEY WORDS

Airport, pavement, testing, evaluation, maintenance, management
INTRODUCTION

Maintenance and rehabilitation of airside pavements of airports is an important aspect of operating safer and efficient air transport systems for any country. Pavement evaluation in terms of functional and structural characteristics plays a vital role in maintenance and rehabilitation planning. Functional evaluation in terms of visual pavement condition rating provides necessary data only for short term maintenance planning. Structural evaluation in terms of non-destructive tests or destructive tests, with material testing, will provide the necessary data for predicting pavement performance and remaining structural life of the pavement structures for long term rehabilitation planning.

Lima Airport Partners (LAP) contracted the consultant to provide the following services at Jorge Chavez International Airport in Lima, Peru; the project involved structural condition evaluation, Pavement Classification Number (PCN) calculation of airside pavements and Pavement Condition Index (PCI) evaluation of the runway of Jorge Chavez International Airport (LIM).

The scope of the project included the following tasks:

- Non-destructive testing of airside pavements using Heavy Weight Deflectometer (HWD)
- Pavement Condition Index (PCI) evaluation of Runway 15-33
- Destructive testing to determine pavement thickness, in situ subgrade strength in terms of Dynamic Cone Penetrometer (DCP) testing, moisture content and classification of materials and concrete compression strength
- Backcalculation of pavement deflection test data to determine the following:
  - Identification of homogeneous sections
  - Structural Life of each homogeneous section
  - PCN value of each homogeneous section
  - Analysis of condition of the different layers of the pavement

This paper describes the methodology of using non-destructive testing for structural condition evaluation and establishing PCN values for different pavement areas of the airport.

According to the information gathered, Jorge Chavez International Airport was constructed in early 1960. The airport consists of one runway (Runway 15-33), one parallel taxiway (Taxiway A and F), four Connector taxiways (Taxiway B, C, D and E) and a terminal apron. All airside pavements are rigid, with 7.5x7.5 meter slab size and around 300 mm of thickness. There are two apron areas (North Black Zone and South Black Zone) and some newly constructed apron areas composed of asphalt concrete. The Runway 15-33 has been rehabilitated with a thin asphalt overlay over a reinforcing glass grid.

NON-DESTRUCTIVE DEFLECTION TESTING

Conducting a pavement evaluation study at an international airport with a single runway was a challenging task. Since non-destructive deflection testing only takes few minutes to complete at a test point, the equipment can be moved from the active airside areas very quickly if a need arise. Further, most of the testing was performed at night when the aircraft
traffic is relatively less. Careful planning and the fullest support from the airport operations personnel are essential for successful completion of this type of study.

Non-destructive deflection testing was performed in accordance with the procedures given in FAA Advisory Circular AC 150/5370-11A (1) and ASTM standard ASTM D-4694 (2). A Heavy Weight Deflectometer (HWD) was used for non-destructive tasks included in this project. The HWD is listed in Appendix 2, Table 1 of the FAA Advisory Circular AC 150/5370-11A (1) as an acceptable device for this application. Figure 1 shows a picture of the HWD.

The Heavy Weight Deflectometer is one of the world’s most accurate deflectometer systems. This accuracy is crucial for the correct analysis of the deflection bowl. It maintains accuracy criteria with allowable systematic errors of only +/- 2% or less of both load and deflection readings. Without this accuracy it is not possible to determine the influence of the upper layer of the pavement from the lower layers. Subgrade influence accounts for approximately 60 – 80% of the total deflection. Thus without the ability to separate the layers accurately considerable errors can result.

The system must be able to simulate the loads necessary to mimic the type of aircraft utilizing the runway. Obviously, the closer the load simulated by the HWD is to the actual one, the less empirical relationships have to be utilized.

Each test location was loaded 3 times with three load levels; 180 KN, 230 KN and 270 KN. The load was applied through a circular plate with a 225 mm radius. Under each impulse load, the resulting pavement surface deflections were recorded at various fixed distances from the center of the circular load plate. These distances were 0, 300, 450, 750, 1,200, 1,500, and 1,800 mm. These deflections along with their distances form a profile of the deflected pavement surface commonly known at a “deflection basin”. The magnitude and shape of the deflection basin is a function of the pavement layer thicknesses and material properties.

On PCC pavements, one transverse joint, one longitudinal joint and one corner was tested to determine load transfer efficiency across the joints and corners as well as subgrade/subbase support condition at joints and corners. Figure 2 shows a typical HWD deflection sensor configuration for joint testing. Alternative deflection sensor configurations can be used depending on the number of active sensors.
The HWD-generated load-deflection data was analyzed using “analytical-empirical” methodology, through a specially developed software package (3), designed to accomplish the task in the best and most efficient manner available. The system is “analytical” in the sense that actual, in-situ material properties and wheel load responses are derived through a reverse, layered analysis technique, as described below. It is still “empirical”, however, in the sense that the relationships between the load related response of these mechanistic or analytical properties and future pavement performance is based upon past experience (observed performance) and associated research. FAA Advisory Circular AC 150/5370-11A, Appendix 2, Table 16 (1) lists several software programs that can be used in the analysis as a candidate back calculation software for this type of analysis.

The selected program back calculates the mechanistic material properties of a uni-axial, semi-infinite pavement system (i.e., the elastic moduli or “E”-values of each structural layer in the pavement). Further, by following a specific testing sequence on concrete pavements, it is capable of determining load transfer at joints and corners, modulus of subgrade reaction at slab centers, joints, corners and screening for the presence of voids under the concrete slabs.

Based on the derived E-values (for each and every HWD test point), the design life and/or needed overlay to bring the pavement up to its design life standard are calculated. The program is able to assign various (user controlled) seasonal adjustments to the derived E-values (e.g., a lower rainy season subgrade modulus), and then calculate the expected remaining service life of the pavement section, and (e.g.) an overlay design if the expected lifetime is inadequate, based on certain “transfer functions” (which are also user controlled). These transfer functions are primarily based on laboratory measured performance correlated with subsequent field observed performance obtained for various pavements. When the fundamental structural pavement properties, i.e. E-values, have been determined, the critical stresses and strains in the structure may be calculated.

As indicated, the prediction of pavement performance (roughness or cracking) from the calculated pavement response (critical stresses and strains) is empirical. The empirical relationships between the derived mechanistic material properties and performance are, however, user controlled. The program therefore may be used for any specific local environmental conditions if these relationships are known.
It should be noted that generally most of the measured magnitudes of deflection are due to the response of the subgrade. It is therefore very important that the subgrade modulus is accurately determined. A small error in the subgrade modulus will lead to a very large error in the derived concrete modulus. For this reason, it is necessary to consider any non-linearity of the subgrade, which can be done quite easily with the analytical-empirical method, using the highly accurate deflection data obtained from a Heavy Weight Deflectometer (HWD) Test System.

Due to the large influence of the subgrade on the measured deflections, it is very important that the deflections are measured at a load level similar to that resulting from design load levels, and that the deflections measured at large distances from the loading center (≥ 1 m) are measured very accurately. With the HWD Test System, deflections are measured to a guaranteed absolute dynamic (under the FWD loading conditions) accuracy of 2% ± 2 microns (0.08 mils), and a typical absolute accuracy of 1% ± 1 micron (0.04 mils).

**Estimation of Pavement Layer Moduli**

The basic analysis process of deflection test results is based on the theory that the stress bowl under the load area expands radially with depth as shown in Figure 3. It can be clearly seen from Figure 3, the furthest deflection measurement represents the deflection in the subgrade and the deflection measurements at the center of the load represent the overall pavement condition (comprising both layer thickness and relative layer stiffness).

The pavement layer moduli are estimated from the deflection test results using backcalculation methodology. The backcalculation involves calculation of theoretical deflections under the applied load using assumed pavement layer moduli. These theoretical deflections are compared with measured deflections such as those shown in Figure 3. The assumed moduli are then adjusted in an iterative procedure until theoretical and measured deflection basins match acceptably well.

Equations for calculating stresses, strains and deflections in a homogeneous, isotropic, linear-elastic semi-infinite space under a point load were first published by Boussinesq in 1885 (6). These original equations were later modified through mathematical integration to approximate the effect of a circular distributed load on a pavement surface such as the load from an FWD.
These modified equations can be directly used to estimate the modulus of the subgrade, if the deflection tests were conducted on the subgrade.

In 1949 a method transforming a system consisting of layers with different stiffness to an equivalent system where all the layers have the same stiffness was proposed by Odemark (6). This system known as the Method of Equivalent Thickness (MET) allowed Boussinesq’s equations for an elastic half space (one homogeneous material) to be used to predict stresses, strains and deflections in layered systems such as road pavements. For example for a two layered system with layer stiffness \( E_1 \) (layer 1) and \( E_2 \) (layer 2), when calculating the compression above the interface of the layers the system is treated as a half space with stiffness \( E_1 \). When calculating stress, strains and deflections at or below the interface the layer above the interface are transformed, using the following equation, into an equivalent layer with stiffness \( E_2 \):

\[
h_e = f \times h_1 \times \sqrt{\frac{E_1}{E_2}}
\]

Where:
- \( h_e \) = The equivalent thickness of one layer.
- \( h_1 \) = The thickness of layer one.
- \( E_1 \) = Stiffness of layer one.
- \( E_2 \) = Stiffness of layer two.
- \( f \) = 0.8 except for the first structural interface where
- \( f_i \) = 0.9 for a 2-layer system (a pavement layer on the subgrade), and
- \( f \) = 1.0 for pavements with more than 2 layers (including the subgrade).

The Odemark’s method provides a very fast algorithm to compute pavement response when compared to modern finite elements programs, which were developed to accommodate non-linear characteristics of pavement materials.

Although elastic theory can be used to predict the stresses and displacements at the centre of a slab, it cannot be used at joints, as the pavement cannot be assumed to be infinite in the horizontal direction. In 1925, Dr. H. M. Westergaard modelled jointed concrete pavements as an elastic plate supported on a spring (Winkler) foundation, modifications of this model are still widely used today (6). The main assumptions made in Westergaard’s model are:

- The concrete slab acts as a homogeneous isotropic solid in equilibrium.
- The reactions of the subgrade are vertical and are proportional to the deflection of the slab.
- The reaction of the subgrade per unit area at any given point is equal to the constant \( k \) multiplied by the deflection at the point. The constant \( k \) is termed the modulus of subgrade reaction and is assumed to be constant at each point, independent of deflection and to be the same at all points within the area considered.
- The thickness of the slab is uniform.
- The load at the interior and the corner of the slab is distributed uniformly over a circular area of contact, for the corner loading the circumference of this circular area is tangent to the edge of the slab.
- The load at the edge of the slab is distributed uniformly over a semi-circular area.

The selected back calculation program uses a deflection basin fit approach together with Odemark-Boussinesq method to estimate pavement layer moduli values based on the deflection results.

PCC modulus of jointed concrete pavements is determined using the same approach as above and Westergaard equations are used to determine the modulus of subgrade reaction (k-value) and to analyze the conditions at joints and corners.

A typical layer moduli plot for an asphalt overlaid PCC pavement is shown in Figure 4.

![Figure 4: Typical Pavement Layer Moduli Plot](image)

**PCC Joint Analysis**

Load transfer values at joints, which are an indicative of joint condition, were calculated for each deflection basin at joints using the FAA guidelines Load Transfer Efficiency (LTE) was computed according to the equations (Equation 15 of FAA Advisory Circular AC 150/5370-11A (1));

\[
LTE = \frac{D_{\text{Unloaded}_{\text{slab}}}}{D_{\text{Loaded}_{\text{slab}}}} \times 100
\]

Where \( D_{\text{Unloaded}_{\text{slab}}} \): Deflection on adjacent unloaded slab in microns

\( D_{\text{Loaded}_{\text{slab}}} \): Deflection on loaded slab in microns

The theoretical load transfer values may range from 0 percent (none) to 100 percent (full). The joint condition can be generally classified based on the following load transfer values: Good 75-100%, Fair 50-75%, and Poor <50%. If joint performance is poor faulting is likely. Figure 5 shows a typical load transfer plot for a PCC pavement.
Figure 5: Typical Load Transfer Plot for PCC Pavement

**Pavement Remaining Life Estimates**

The selected software was used to estimate pavement remaining life and overlay requirements at each HWD test point. The estimated moduli are adjusted to reflect conditions representative of each season for the design period. For each season, asphalt moduli can be calculated as a function of temperature; while moduli of unbound materials (including the subgrade) are a function of the time of year in relation to spring thaw or wet period, if applicable.

Critical stresses and strains are calculated and Miner's law is used to sum the damage caused during each season by each load, based on user-defined damage (fatigue or rutting) relationships. The program then calculates the expected remaining life of the pavement, and the overlay thickness required using a specified overlay material for a given design period.

Transfer functions relate traffic loading to pavement deterioration. Wheel loads transfer stresses into the pavement structure. Materials develop strains which are a function of the stresses applied by the loading wheel(s) and the modulus of the various layers in the pavement structure.

Two types of pavement deterioration are modeled in the software- cracking of bound layers and permanent deformation for unbound layers. Bound layers consist of materials that are composed of aggregates held together by a binder such as asphalt or Portland Cement Concrete (PCC). Bound materials can develop tensile stresses. Unbound materials may be granular, composed of aggregates or particles that are compacted and held together through (primarily) inter-particle friction, or cohesive (clay). Granular materials typically cannot develop tensile stresses.

The primary distress mode for bound layers is usually fatigue cracking, which is related to the magnitude of the repeated stresses or strains at the bottom of the pavement layer. Cracking in asphalt pavements has been found to correlate well with repeated tensile strains. Cracking in Portland cement stabilized layers has been found to correlate well with repeated tensile stresses.
The primary distress mode for unbound layers is usually through permanent deformation which results in either rutting or poor ride quality (roughness), or both. Permanent deformation has been found to correlate well with repeated vertical compressive strains at the top of the unbound layer.

**Pavement Damage Criteria**

For purposes of the analyses, the most important equations and parameters are as follows.

1. Moduli values of the sub-base and subgrade were assumed constant throughout the year.
2. Ratio between static and dynamic (effective) load = 1.2
3. Rigid pavement design fatigue failure criteria:
   \[
   \sigma_{PCC} = 2.768 \times N^{-0.058} \times (E/30,000)
   \]
   where:
   - \(\sigma_{PCC}\) = Tensile stress at bottom of PCC slab,
   - \(N\) = No. of aircraft gear load repetitions,
   - \(E\) = Modulus of PCC (Mpa),
   
   This is a regression relationship based on the Portland Cement Association (PCA) criterion (6).
4. Flexible Pavement Design Criteria
   \[
   \varepsilon = 214 \times N^{-0.2} \times (E/3000)^c
   \]
   where,
   - \(E\) = Modulus of asphalt (Mpa)
   - \(c\) = -0.533
   
   This is a regression relationship based on the U.S. Army Corps of Engineers for Airfield Pavement Design (3).
5. Permissible stress on all unbound materials (rutting):
   \[
   \sigma_{1,p} = 0.117 \times N^{-0.307} \times (E/E_0)^c
   \]
   where:
   - \(E\) = Modulus of material (Mpa)
   - \(E_0\) = 160 Mpa
   - \(c\) = 1 for \(E > E_0\)
   - \(c\) = 1.16 for \(E < E_0\).

6. Assumed design life = 20 years
7. Twelve seasons were assumed and the average monthly temperatures found in Lima, Peru region were used for asphalt concrete temperature-moduli variation.
8. Aircraft types and number of operations were obtained from the information provided by Lima Airport Partners.

In summary, to determine the remaining life of the pavement using deflection results, the program first calculates the seasonal moduli for each pavement materials at each season. Figure 6 shows plot of seasonal moduli values for the AC pavement layer for a typical FWD test line along a runway.
The second step of the process includes calculating pavement response for each of the aircraft types. Figure 7 shows a typical plot of tensile stress at the bottom of the PCC layer due to a MD-11 aircraft loading.

Finally, the program sums the pavement damage caused during each season, by each load, based on the defined pavement damage criteria using Miner’s law. Then the program calculates the expected remaining life of the pavement and if it is less than the design period program calculates the needed overlay.

**PCN EVALUATION**

The Aircraft Classification Number (ACN) is defined by ICAO, using a "mathematically derived single wheel load to define the landing gear/pavement interaction. "Aerodrome Design Manual – Part 3 – Pavements", Second Edition 1983 (4), by the International Civil Aviation Organization (ICAO) defines the Pavement Classification Number (PCN) as "A number expressing the bearing strength of a pavement for unrestricted operations".
This is done by equating the thickness given by the mathematical model for an aircraft gear to the thickness for a single wheel at a standard tire pressure of 1.25 MPa". Boussinesq’s equations are used for flexible pavements and Westergaard’s solution for a plate on a Winkler foundation for rigid pavements (3).

PCN values are reported as a five part code as follows:

Part 1: The PCN Number: The highest permitted ACN at the appropriate subgrade category
Part 2: The type of pavement, R=rigid, F=flexible
Part 3: The pavement subgrade category, A=high, B=medium, C=low, D=ultra low
Part 4: The maximum tire pressure authorized for the pavement, W=high (no limit), X=medium (limited to 1.5 Mpa), Y=low (limited to 1.0 Mpa, Z=very low (limited to 0.5 Mpa)
Part 5: Pavement design/evaluation method, T=technical design, U=by experience

For flexible pavements the thickness is determined from the CBR value, using the equation:

\[ t = \frac{DSWL}{\sqrt{0.5692 CBR - \frac{DSWL}{32.035 \times P_s}}} \]

where
- \( t \) is the thickness in cm,
- \( DSWL \) is the single wheel load in kg, and
- \( P_s \) is the tire pressure (1.25 MPa).

The ACN is two times the derived single wheel load in 1,000 of kg. The ACN is calculated by the aircraft manufacturer for 4 subgrade categories (A: CBR > 13, B: 8 < CBR < 13, C: 4 < CBR < 8 and D: CBR < 4). The ACN is specific to a particular aircraft and does not depend on the number of operations (the equation above is for 10,000 coverages) on the pavement structure (apart from the subgrade category).

For rigid pavements, a standard stress for reporting purposes is stipulated (\( s = 2.75 \) MPa) only as a means of ensuring uniform reporting of ACN. The working stress to be used for the design or evaluation of pavements has no relationship to the standard stress for reporting. For rigid pavements the subgrade categories depend on the modulus of subgrade reaction (the k value determined using a 750 mm diameter plate). The four categories are: A: k > 120 kPa/mm, B: 60 kPa/mm < k < 120 kPa/mm, C: 25 kPa/mm < k < 60 kPa/mm and D: k < 25 kPa/mm.

Pavements deteriorate gradually under the effects of loading and climate. Both the size of the loads and the number of load repetitions are important for the rate of deterioration. The PCN of a given pavement structure will, therefore, depend not only on the pavement structure itself, but also on the expected number of load repetitions. If "unrestricted operations" corresponds to a large number of load repetitions, the PCN will be lower than if it corresponds to a more limited number of repetitions.


**Design Aircraft**
The Design Aircraft is normally the aircraft with the highest ACN on the actual subgrade. This design ACN should be related to the actual value of the subgrade under the pavement. The actual subgrade strength values determined using HWD test results were used to determine the ACN of the Lima Airport fleet mix. The aircraft with the highest ACN value was selected for each pavement area. Each aircraft in the Lima Airport fleet mix were considered to select the design aircraft.

When the fleet mix includes a variety of aircraft, the “ICAO-PCN/ACN” method describes a method to relate the loading severity of each type of aircraft to that of the Design Aircraft. Then the fleet mix can be converted to number of Equivalent Coverages by the Design Aircraft. Different procedures are included for rigid pavements and flexible pavements. The equivalent coverage by design aircraft was determined by using methods given by ICAO manuals and “A Guide to Airfield Pavement Design and Evaluation” developed by United Kingdom Department of the Environment (5).

**Calculation of PCN using FWD deflection Data**
Calculation of the PCN at an FWD test point has three steps.

1. The layer moduli are derived from the deflection basin, at the conditions of the test
2. The design moduli are determined for each season considered in the design
3. The single wheel load that will correspond to the damage criterion for the subgrade, at the specified number of load repetitions, is derived and converted to PCN in the same way as for ACN.

The damage is accumulated for all seasonal conditions using Miner’s law, and the PCN is determined as two times that single wheel load, in thousand kilograms, that will correspond to the criterion expressed as:

\[
\sigma_{\text{permissible}} = A \times \left( \frac{E}{E_{\text{reference}}} \right)^B \times \left( \frac{N}{10^4} \right)^C
\]

where \( E \) is the modulus.
\( N \) is the number of load repetitions, and
\( A, B, C \) and \( E_{\text{reference}} \) are constants.

For flexible pavements the criterion refers to the stress at the top of the subgrade, while for rigid pavements the criterion used, is for the tensile stress at the bottom of the concrete slab. For rigid pavements only tests at slab centers are considered.

Figure 8 illustrates a typical plot of PCN-ACN values. The variation of ACN is due to the variation of subgrade modulus along the FWD test line. The PCN variation is due to the condition of the pavement structure along the FWD test line.
CONCLUSIONS

Pavement evaluations to plan future maintenance/rehabilitation activities are extremely important to protect billions of dollars worth of pavement asset in an airport. Pavement evaluations can be performed using destructive or non-destructive methods. Non-destructive evaluations with limited destructive tests are extremely popular due to its relatively speedy process and minimum damage to the pavement structures. Further, recent technological advances in non-destructive test systems, pavement engineers realized the advantageous of using non-destructive testing for pavement evaluations.

A specialized pavement analysis software was used to determine pavement layer properties, remaining life of the pavement structure and Pavement Classification Number (PCN) of pavement structure at each HWD data point. This program estimates pavement layer moduli values based on the deflection results using a deflection basin fit approach together with Odemark-Boussinesq method. PCC modulus of jointed concrete pavements is determined using the same approach as above and Westergaard equations are used to determine the modulus of subgrade reaction (k-value) and to analyze the conditions at joints and corners.

Determination of remaining life of the pavement structure using HWD test results follows a three step procedure. First, the program calculates seasonal layer moduli of different pavement layers based on defined environmental changes during the year. Secondly, the program calculates the pavement response due to different aircraft loadings at each season. Finally, the program sum the pavement damage caused during each season, by each load, based on the defined pavement damage criteria using Miner’s law. Then the program calculates the expected remaining life of the pavement and if it is less than the design period program calculated the needed overlay.

PCN values for the pavement structures were determined using guidelines provided in the "Aerodrome Design Manual – Part 3 – Pavements", Second Edition 1983 (4), by the International Civil Aviation Organization (ICAO). Calculation of the PCN at an FWD test point also has three steps. First, the layer moduli are derived from the deflection basin, at the
conditions of the test. Secondly, the design moduli are determined for each season considered in the design. Finally, the single wheel load that will correspond to the damage criterion for the subgrade, at the specified number of load repetitions, is derived and converted to PCN in the same way as for ACN.

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