AIRPORT PAVEMENT EVALUATION

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ABSTRACT

Air traffic has increased tremendously over the last thirty years. As a result, many airports have experienced a continuous cycle of upgrade and expansion. Pavement evaluation methods have evolved and become an integral part of the design and rehabilitation process. Some of the unique issues associated with airport evaluation include the complex loading conditions and multi-layer pavement systems. Aircraft gross loads are continuing to increase and individual wheel loads are approaching the entire weight of a truck for which a highway pavement might be designed. In addition to the load magnitude, there are the issues associated with complex gear geometry, high tire pressures, and how to account for the effects of mixed traffic. Because of increased traffic volumes and cost to an airport for facility closures, non-destructive testing has become the preferred method for assessing the condition of existing pavements. A variety of assessment tools is now available, each having both advantages and limitations. The International Civil Aviation Organization's aircraft classification number-pavement classification number (ACN-PCN) procedure has been widely accepted. However, some interesting issues have been raised with respect to the ACN (specifying the effect of new heavy aircraft) and interpreting the PCN (load bearing capacity of the pavement). In many ways, the requirement for determining structural capacity and predicting performance under increased traffic has driven the development of new design procedures and testing equipment. This paper discusses the evolution of airport pavement evaluation methods and describe the current state-of-the-practice.

KEY WORDS

AIRPORT / PAVEMENT / EVALUATION / NON-DESTRUCTIVE TESTING / CLASSIFICATION

1. INTRODUCTION

There are millions of square metres of existing airport pavements worldwide, and a knowledge of how they will perform in the future is a vital part of long-term planning for airports. Given the areas of existing pavements compared to new pavements constructed each year, it is arguably a more important issue than new pavement design.

Airports need to know:

- what aircraft can use a pavement,
- how many of them,
- for how long,

- what rehabilitation or strengthening will be required at the end of the pavement life.

These issues are far more complex than for roads because of the range of aircraft loading (Section 2), and the complexity of many airport pavement structures (Section 3).

No site or laboratory testing can directly predict future performance, so a pavement evaluation therefore has two components

- A structural investigation to determine the necessary pavement and subgrade properties (Figure 1).

- Determination of the pavement strength and residual life by reverse design using one of the available design and evaluation methods, described in Section 6.

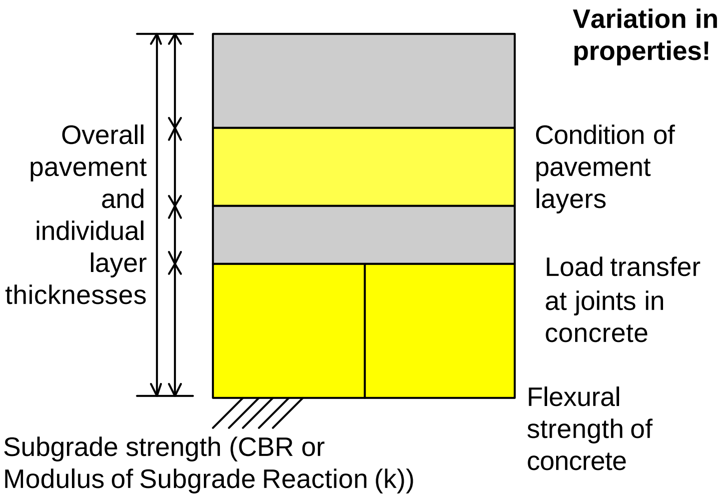

Figure 1: Information required from structural investigations.

Increasing site access restrictions, and a requirement for improved accuracy in pavement testing has driven a search for replacements for the historical test methods described in Section 4.1, and a new generation of methods such as the Falling Weight Deflectometer and Ground Penetrating Radar are now in use. These methods are described in Section 4.2.

Once a pavement has been evaluated the results have to be reported in a meaningful way. The international standard is the ICAO ACN-PCN method, described in Section 7. This method has limitations which are discussed in detail.

This paper discusses the factors involved in airport pavement evaluation, including aircraft traffic, pavements, test methods (in particular the Falling Weight Deflectometer) and reverse design, reporting of pavement strength and future developments.

2. AIRCRAFT TRAFFIC

Loading on roads is largely fixed by the road operators as some form of maximum axle load, with a very small proportion of loads being heavier, abnormal loads. In comparison aircraft manufacturers have driven a steady increase in aircraft loading on airport pavements over the last 50 years, expecting airport operators to provide increasing pavement strength to match the aircraft loading.

Aircraft gross loads are continuing to increase and although manufacturers are adding extra undercarriage struts and wheels to help control the damaging effect on the pavement, strut loads and wheel loads are also increasing (Figure 2). Individual wheel loads are approaching the entire weight of a truck for which a highway pavement might be designed. In addition to the load magnitude, there are the issues associated with complex wheel gear geometry (Figure 3) and high tire pressures (up to 15 bar (220 psi) on civil aircraft and 22 bar (325 psi) on military aircraft.

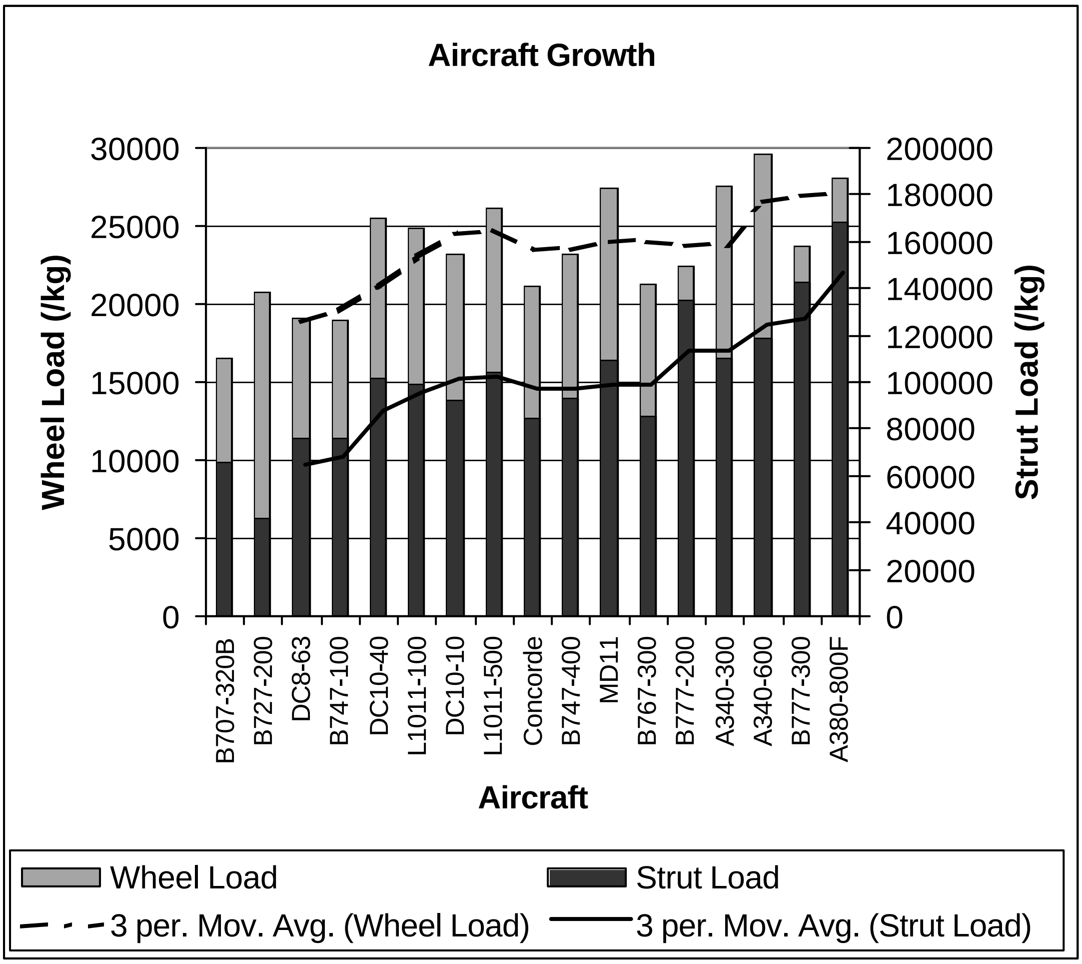

Figure 2. Growth in Aircraft Wheel and Strut Loads.

Increasing loads and more complex wheel geometry lead to two significant problems:

1. New loads are outside the range of previous experience so that historical empirical relationships may no longer apply.

2. The loads cannot be practicably reproduced in routine testing. Pavement behaviour measured by test loads must therefore be correctly extrapolated to heavy aircraft loading by the reverse design method used, including correctly dealing with any load dependency.

Figure 4 shows wheel loads and tire pressures for a number of civil and military aircraft. The shaded box shows a comfort zone in which there is sufficient historical experience to give a reasonable degree of confidence that design and evaluation methods work.

Outside this box there are a number of aircraft for which additional experience is necessary before we can be comfortable that current methods are adequate.

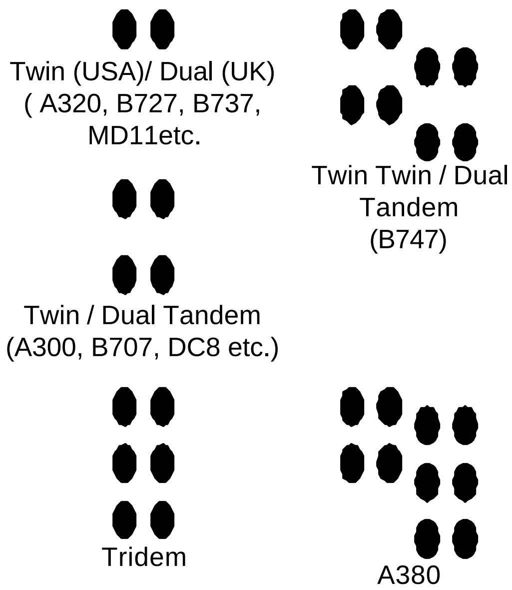

Figure 3. Main wheel gear layouts.

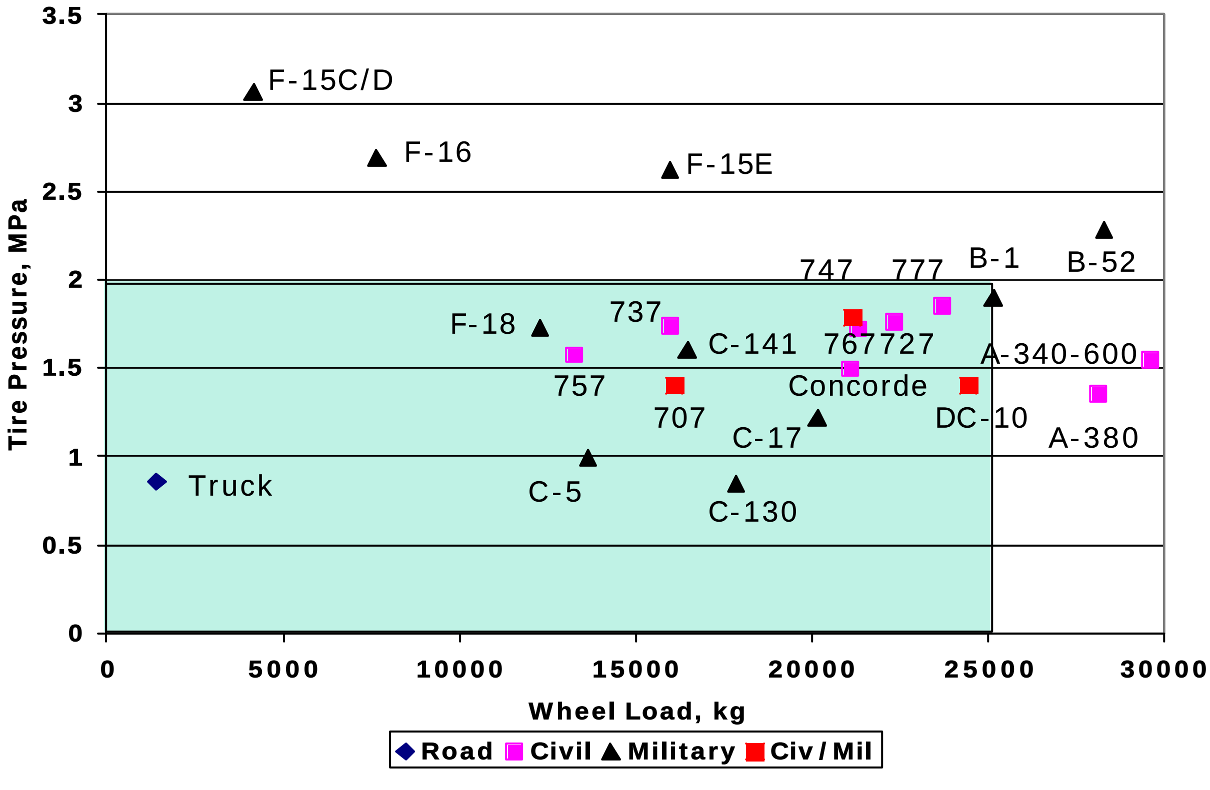

Figure 4. Current comfort zone.

In addition to increasing aircraft loads, the number of aircraft movements has been increasing and major growth is predicted for several decades to come, increasing demands on existing pavements.

For roads, where damage is done by a very small range of significant loads, pavement strength and life can be simply reported as a number of axle loads. In comparison most airport pavements are trafficked by a mix of aircraft each causing significant damage. There are an infinite number of combinations of load and load repetitions that an airport pavement can carry. Evaluation methods, and some means of reporting pavement strength that can cater for a mix of traffic is therefore required.

3. COMPLEX PAVEMENT CONSTRUCTIONS

It is often practicable to overlay airport pavements, unlike roads where the constraints are generally too great. Many airport pavements have been built up over several generations of construction, due to requirements to restore surface serviceability, strengthen, and re-profile to meet modern standards (Figure 5). Pavement evaluation methods need to cater for a range of construction types, including composite (asphalt on concrete), multiple slab and mixed bituminous-bound and cement-bound layers

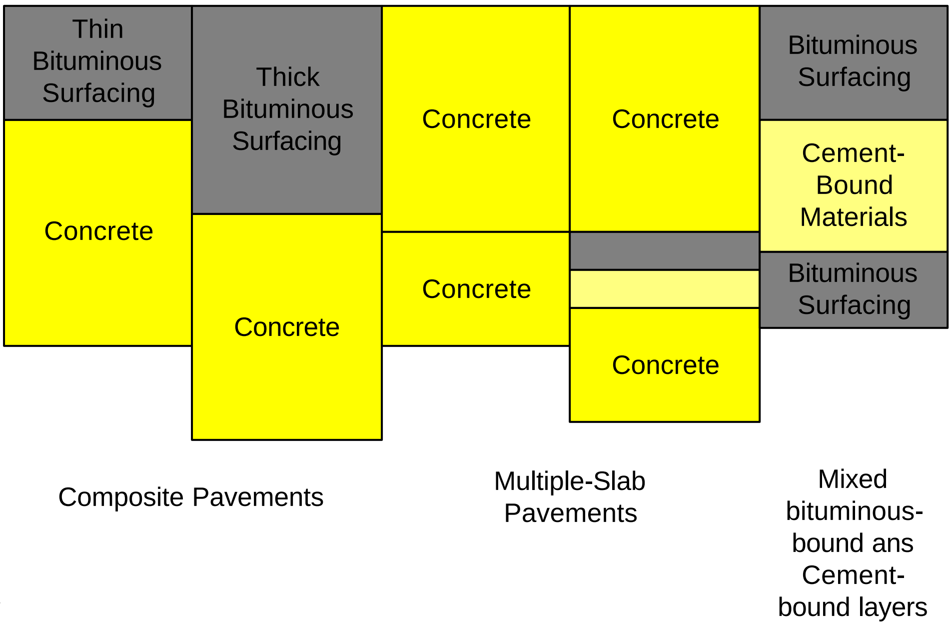

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Figure 6) - and sometimes combinations of all three.

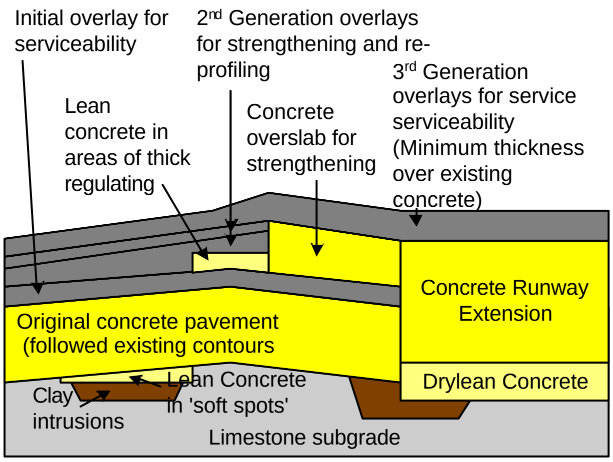

Figure 5. Construction sequence for typical UK runway (highly simplified).

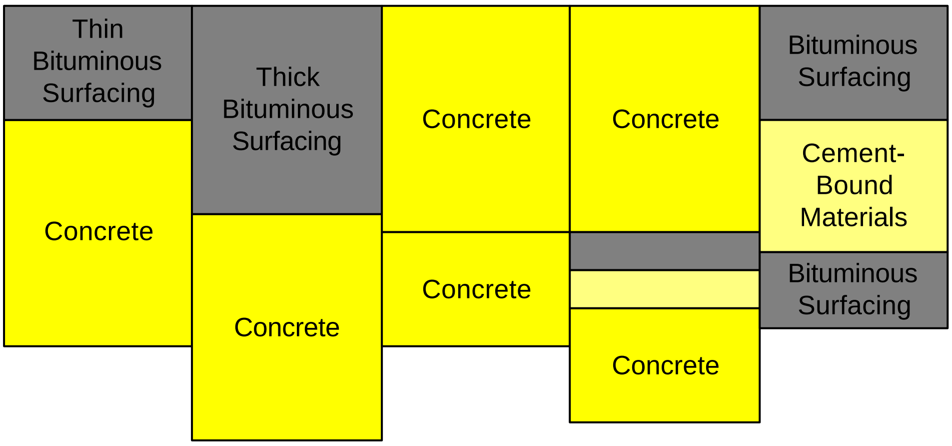

Figure 6. Basic complex pavement types.

Re-profiling from an original pavement following the lie of the land to a surface compliant with modern criteria can lead to enormous variations in thickness, with consequent statistical problems of how to assign a single strength to a variable construction.

Some of these forms of construction cannot be practicably dealt with by so called mechanistic / analytical design processes.

4. HISTORY

4.1. Previous methods

Design methods have incorporated evaluation and sometimes site investigation methods since the 1940s. Some of the major site investigation methods used to date have included:

- Rolling.
- Plate bearing tests.
- WES 16 kip vibrator, and other vibratory devices such as the Dynaflect and Road Rater.
- Coring / trial pits and subgrade strength tests by plate test or in situ California Bearing Ratio test.

These historical site investigation methods have tended to be one or more of slow, cumbersome, inaccurate, difficult to perform and destructive. Requirements for better test results and increasing access problems have led to a search for faster test methods capable of giving accurate results at more frequent intervals.

4.2. Developments

In the USA, the introduction of aircraft with large wheel loads during the 1940s and 1950s highlighted the need for better methods of pavement evaluation. With aircraft wheel loads increasing rapidly, much of the early work in pavement evaluation was driven by the need for assessing the structural adequacy of new construction, determining the adequacy of existing pavements for changing missions, and developing rehabilitation requirements. These new and more demanding operational requirements differed significantly from highway construction. In early days, pavement evaluation almost certainly involved "direct" sampling to determine pavement layer properties such as thickness, strength, and material type. In many cases, the evaluation required the excavation of test pits for performing in situ tests and obtaining samples for laboratory testing. The result was lengthy pavement closures to obtain an often-limited amount of costly test results. As traffic volumes also increased at many airports, it became evident that rapid, non-destructive methods were needed.

A major advantage of non-destructive testing is that results can be obtained without removing a critical pavement facility from service. Excavation and repair of an adequate number of test pits for direct sampling can result in facility closures of 1-3 weeks. The following example from *Symposium on Nondestructive Test and Evaluation of Airport Pavement* (U. S. Army Engineer Waterways Experiment Station, 1976), illustrates the impact that can be realized. Two runways were closed at a major hub airport on a Friday evening for deflection testing. An unexpected shift in winds on Saturday morning resulted in only two runways being available for sustaining all aircraft operations prior to reopening of one of the closed runways later in the day. Traffic delays from the morning and continued delays after the third runway was reopened resulted in 15,000 minutes of delay for inbound air traffic and an additional 680,000 litres of fuel consumed. With non-destructive testing, both of the runways could have been made available immediately when the winds changed with no runway closure at all.

Nondestructive testing is clearly desirable with respect to costs associated with airport operational disruptions, costs of testing, and the improved reliability resulting from the ability to perform more tests. As a result, a number of NDT devices began to emerge in the 1950s and 1960s. These devices varied widely in operating concepts, loading type, etc. and included vibratory loadings, wave propagation measurements, and deflection measurements for determining pavement properties that could be used to predict pavement performance or that could be correlated to pavement performance. In recent years, the steady state vibratory loading methods have been overshadowed by falling weight deflectometers that can induce loads near the actual aircraft loads and are much more transportable. The U.S. Army Engineer Research and Development Center (ERDC) has developed methodologies for determining the load carrying capacity of pavements using non-destructive test results. These procedures, documented in *Airfield Pavement Evaluation* (Headquarters, Departments of the Army, Navy, and the Air Force, 2001), have been used extensively since the mid-1980s for the evaluation of U.S. military pavements.

In the UK, the Property Services Agency, then responsible for construction and maintenance of all military airfields, researched the use of the Falling Weight Deflectometer between 1985 and 1987, and adopted it as a standard test method in 1987 with the purchase of a Heavy Falling Weight Deflectometer. Since then the Falling Weight Deflectometer has become the most common test method for airport pavements in the UK.

Ground Penetrating Radar also appeared in the late 1980s, but took some years before it made much progress. However, Ground Penetrating Radar, backed up by cores for calibration, can now provide rapid and accurate layer thicknesses for airport pavements.

The other major change in the 1980s was the adoption in the USA and UK of the Dynamic Cone Penetrometer (with an 8 kg drop weight and 575 mm drop height, originally developed in South Africa) as a standard method for testing subgrade strength, largely replacing both in situ CBR tests and plate tests. This has led to the development of the mechanized DCP in the USA.

Regardless of the non-destructive test methods selected for a site investigation, coring is still necessary to obtain layer thicknesses or to calibrate Ground Penetrating Radar results, to allow subgrade strength tests and to obtain samples for concrete strength testing.

Concrete strength is a key parameter in the evaluation of rigid or composite airport pavements, and yet current methods for estimating flexural strength based on relationships with indirect tensile or compressive strength from cores are inaccurate. The adequacy of strength estimates is further limited by the difficulty in obtaining sufficient samples. It is ironic that developments in non-destructive testing aimed at decreasing requirements for coring also decrease the number of samples for concrete strength testing and therefore the accuracy of the result.

Descriptions of current site investigation methods based on these developments can be found in *Use of Nondestructive Testing in the Evaluation of Airport Pavements* (FAA, 2003) and *Guidance note on structural investigations of airfield pavements* (Defence Estates, 2002).

5. FALLING WEIGHT DEFLECTOMETER

The FWD applies an impact load to the pavement surface, and the pavement response in terms of deflection is measured at several radial locations from the load centre. The measured deflections can be used in a number of ways, including:

1. Qualitative analysis of pavement variability, to find homogenous pavement sections.

2. Calculation of the Load Transfer Efficiency at joints.

3. Estimation of layer elastic stiffnesses.

In variable pavement constructions analysis of deflection measurements can be used to help determine homogenous sections of pavement, i.e. sections that cannot be further sub-divided into sub-sections with significantly different mean deflections. A homogenous section represents a section of pavement with similar behaviour, and section boundaries may reflect changes in factors such as subgrade strength, pavement construction, layer thicknesses or material condition (Figure 7).

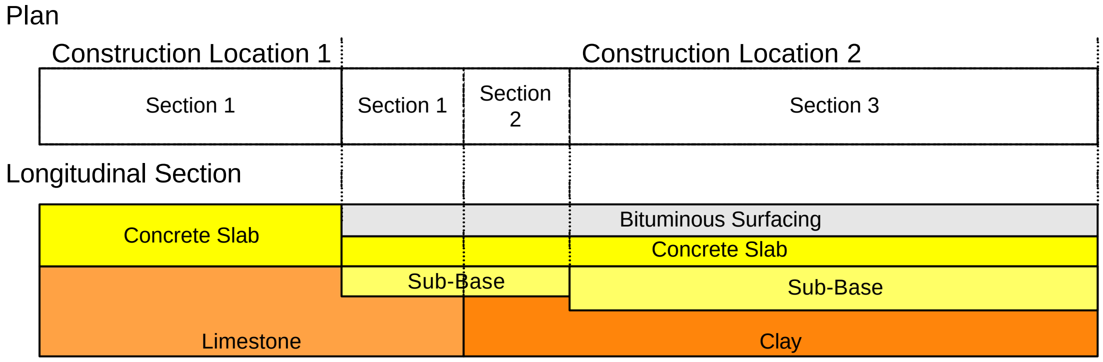

Figure 7. Homogenous Sections.

Various statistical methods are available for analysing results, but the simplest and most visible is the Cumulative Sum approach (Figure 8).

As the magnitude of deflections in different parts of a deflection basin is linked to the behaviour of different parts of the pavement structure and subgrade, selecting different parameters, such as the central deflection, a deflection from one of the outer deflectors, and the difference between two deflectors close to the centre, enables variation in overall behaviour, subgrade strength and bound layer stiffness to be examined.

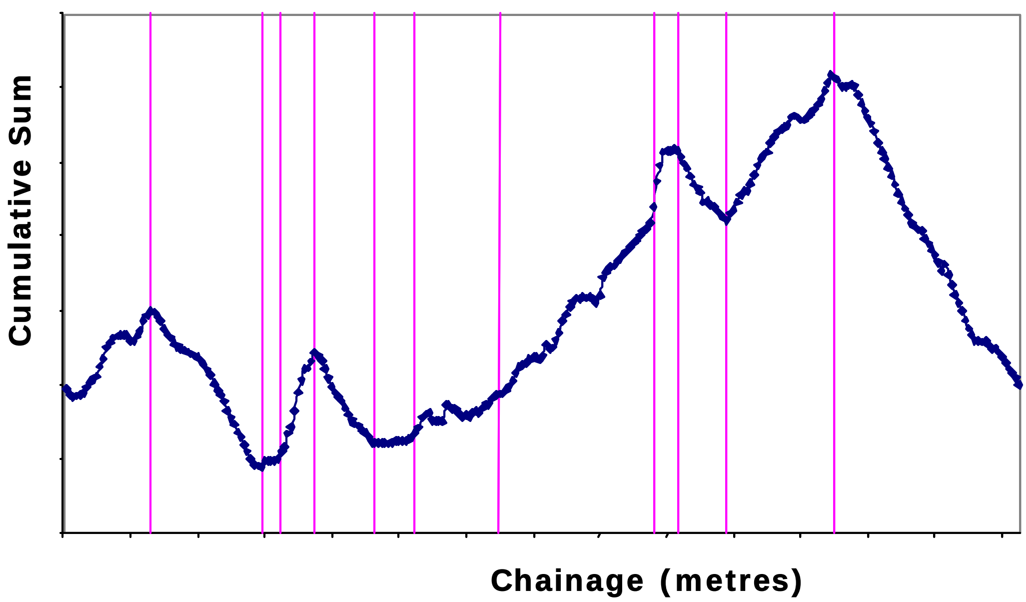

Figure 8. Cumulative Sum Method.

Load Transfer Efficiency at joints in rigid pavements can be assessed by the ratio of deflection measurements on either side of the joint (Figure 9). Although a measure of Load Transfer Efficiency can be obtained from the Falling Weight Deflectometer, it is realized that the results depend on many factors such as the type of joint, pavement age, and temperature gradient in the slab. The ERDC has developed methods, presented in *Airfield Pavement Evaluation* (Headquarters, Departments of the Army, Navy, and the Air Force, 2001), for modifying evaluation results based on the measurement of poor load transfer. It is recommended that joint testing be performed in the early morning before the slabs expand or a temperature gradient develops in order to obtain reasonable approximations of load transfer efficiency. Another alternative is to establish and test a reference slab throughout the day to develop a relationship between air temperature and joint efficiency.

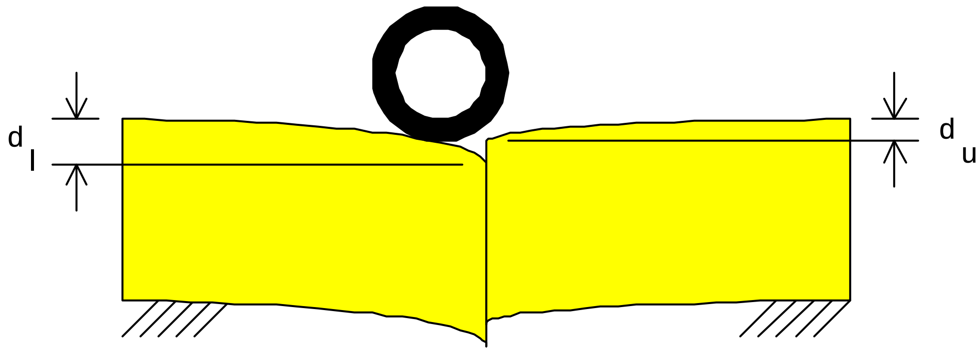

Figure 9. Load Transfer at Joints in Rigid Pavements.

The deflection bowls obtained from the FWD testing can be used as data for the back-calculation of estimated elastic stiffnesses of the pavement layers and subgrade, by matching the measured deflections to computed values. The thickness of the pavement layers, which can be obtained by coring or a Ground Penetrating Radar survey, is required for the analysis process. The back-analysed elastic stiffness can be used to estimate material condition for use with reverse design, or directly in the evaluation calculation.

However, considerable caution is required in the use of back-analysed stiffnesses. For various reasons, it is virtually impossible to obtain an exact match between measured and calculated deflection basins. Results therefore have to be accepted based on matching deflections to within a certain degree of accuracy. Within that accuracy a range of solutions is possible and different back-analysis programs will find different solutions, even if they are using similar forward analysis algorithms to calculate deflections. The extent of the problem is illustrated by Figure 10, which shows back-calculated stiffnesses for the concrete layer in a composite construction, obtained from the same deflection basins and load data by four different back-analysis programmes. It can be seen that back-calculated stiffnesses for the same point vary by a factor of up to 4. It is possible for one program to report a stiffness indicating that the concrete slab is in excellent condition while another indicates that it is shattered. The knock-on effect of differences in back-analysed stiffnesses when layer elastic stiffness is used directly for evaluation is large differences in reported strength or calculated overlay requirements.

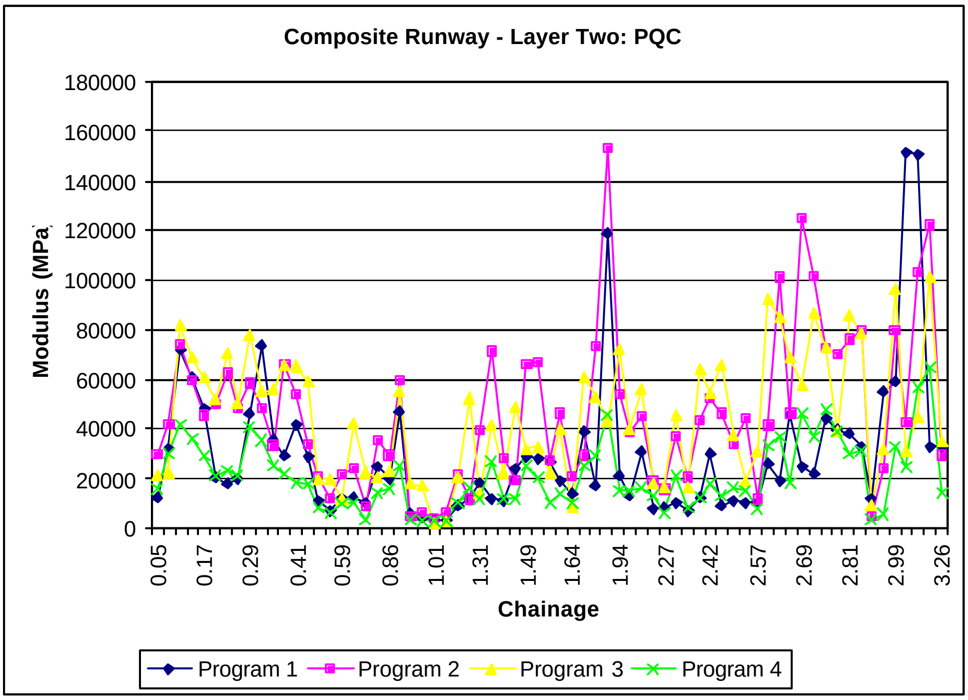

Figure 10. Comparison of back-analysed stiffnesses using various programs.

6. REVERSE DESIGN

On completion of a site investigation the pavement parameters required for reverse design can be determined from the results and then used with an appropriate design method, such as the FAA (FAA, 1995), PSA (PSA, 1989), or ERDC (Headquarters, Departments of the Army, Navy, and the Air Force, 2001) design guides which give comprehensive advice on pavement evaluation and reverse design.

Newer design methods, such as BAA (BAA, 1993), LEDFAA (FAA, 1995), and PCASE (Stet, Thewessen and Van Cauwelaert, 2001), based on Multi-Layer Elastic Analysis can also be used for reverse design in conjunction with back-analysed layer stiffnesses. However, the caveats about back-analysis given in Section 5 must be taken into account, and these methods cannot deal with pavements where layer condition is allowed to change significantly with time (e.g. composite pavements where the concrete slab is allowed to progressively crack before failure) and some other situations such as complex multiple slab pavements.

A critical factor in pavement evaluation is the estimation of passed and future traffic. To deal with traffic mixes with a range of aircraft types a suitable mixed traffic analysis method is required.

7. REPORTING AIRPORT PAVEMENT STRENGTH - THE ACN-PCN METHOD

For many years, the weight bearing capacity of airfields has been published in various documents such as Flight Information Publications (FLIP) and Aeronautical Information Publications (AIP). The reported values were often confusing due to the variety of reporting systems that included aircraft designation, single wheel load, equivalent single wheel load, load classification number (LCN), and loads for single, dual, and dual tandem gear. The aircraft classification number (ACN) – pavement classification number (PCN) system was adopted by the International Civil Aviation Organization (ICAO) in 1983 (ICAO, 1983) and provides a standardized means of reporting a pavement load-carrying capacity. This method also provides a means of easily translating the reported value into an allowable load for any aircraft. The ACN and PCN are defined as follows: The ACN is a number which expresses the relative structural effect of an aircraft on both flexible and rigid pavements for specific standard subgrade strengths in terms of a standard single wheel load. The PCN is a number which expresses the relative load-carrying capacity of a pavement for a given pavement life in terms of a standard single wheel load. The PCN consists of five components: the numerical PCN value indicating the load-carrying capacity, the pavement type (rigid or flexible), the subgrade strength category (high, medium, low, or ultra-low), the tire pressure code (high, medium, low, ultra-low), and the source (technical evaluation or using aircraft).

The system works by comparing the ACN to the PCN. The PCN is a representation of the allowable load for a specified number of repetitions over the life of a pavement. The ACN is a representation of the load applied by an aircraft using the pavement. The system is structured such that an aircraft operating at an ACN (applied load) equal to or less than the PCN (allowable load) would comply with load restrictions established based on a specified design life for the pavement facility. If, however, the ACN (applied load) is greater than the PCN (allowable load), the specified design life will be shortened due to this overloading. ICAO provides only general guidelines for handling the overload situation. Pavements can usually support some overload; however, pavement life is reduced. As a general rule, limited operations at ACN/PCN ratios of 1.0 to 1.25 will have minimal impact on pavement life. If the ACN/PCN ratio is between 1.25 and 1.5, aircraft operations should be limited to 10 passes, and the pavement inspected after each operation. Aircraft operations resulting in an ACN/PCN ratio over 1.5 should not be allowed except for emergencies.

A limitation of the ACN-PCN system is that the five-part code does not include the number of passes that the load-carrying capacity is based upon. For example, a pavement with a specified thickness and subgrade strength can be analyzed as shown in Table 1

Table 1: Effect of Desired Life on PCN

Desired Life (Aircraft Repetitions)	**Allowable Load (kg x 1000)**	**PCN**
1000	190.5	90
50,000	*128.4*	*55*
…	…	…
100,000	121.5	51

The PCN only reflects the allowable load and does not convey the expected life of the pavement. A user of a reported PCN may not know whether limiting the load will result in a life of 1,000 or 100,000 passes. Without knowing the pass level for the PCN analysis, the damage caused by each load application cannot be estimated. Therefore, the PCN numerical value alone may not be adequate for managing or planning of operations that include large numbers of aircraft passes. The ERDC has developed a procedure that uses the design pass level to extend the utility of the ACN-PCN system (Alexander and Hall, 1991). Once a design aircraft and pass level have been determined, additional calculations are made to generate allowable loads for a range of aircraft passes. An ACN/PCN ratio is computed as the ratio of the ACN at a specified pass level to the PCN computed for the design pass level (50,000 passes for this example). The results are illustrated in Table 2.

Table 2: Calculation of damage per aircraft operation

Desired Life (Aircraft Repetitions)	Allowable Load (kg x 1000)	ACN	PCN	ACN/PCN	Damage per Operation
1000	190.5	90		1.64	1/1000
50,000	*128.4*	*55*	*55*	*1.00*	*1/50,000*
…	…	…	…	…	…
100,000	121.5	51		0.93	1/100,000

Plotting the relationship of ACN/PCN versus aircraft passes provides a relatively easy means of estimating the allowable repetitions for any aircraft (ACN). Once the allowable passes are determined for a specified load, the damage/operation can be approximated. Including this plot along with the PCN five part code provides much more information upon which airport operators can use for effectively managing traffic movements and making go-no go decisions regarding the use of a facility by aircraft which normally may not operate on the airport.

8. CONCLUSIONS

Evaluation of airport pavements is more complex than roads because of the wide range of aircraft and wheel loads, and the complexity of many constructions.

Some new aircraft are outside our comfort zone, and more data is required before we can assess the reliability of current design methods.

Access restrictions have driven development of non-destructive testing equipment and methods, but we are still searching for better methods to obtain concrete strength without coring.

Reporting airport weight bearing capacity is a complex and misunderstood subject.

New test methods should strive toward providing parameters compatible with more sophisticated analysis.

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