AEROSPACE INFORMATION REPORT

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(R) Aircraft Flotation Analysis

RATIONALE

Recent regulatory changes have introduced new standards for international flotation calculation and reporting. The document is updated to bring it into line with current and upcoming practice in flotation analysis.

1. SCOPE

This document is divided into five parts. The first part deals with flotation analysis features and definitions to acquaint the engineer with elements common to the various methods and the meanings of the terms used. The second part identifies and describes current flotation analysis methods. Due to the close relationship between flotation analysis and runway design, methods for the latter are also included in this document. As runway design criteria are occasionally used for flotation evaluation, including some for runways built to now obsolete criteria, a listing of the majority of these criteria constitutes the third part. The fourth part of this document tabulates the most relevant documents, categorizing them for commercial and civil versus military usage, by military service to be satisfied, and by type of pavement. This document concludes with brief elaborations of some concepts for broadening the analyst's understanding of the subject. At revision B of this document, significant new material added is adapted from Reference [34], Schmidt, R. Kyle, *The Design of Aircraft Landing Gear*, SAE International, 2020.

1.1 Purpose

This document provides an overview of concepts in flotation, historical approaches, and background on currently accepted methods. For the most recent recommended methods, the reader is referred to ARP1821. An overview of historical cooperation on the flotation topic between SAE and the U.S. Army Corps of Engineers is found in AIR4243.

Aircraft flotation analysis can be characterized by a variety of methods, and this may lead to confusion. Sources of this variety are at least fourfold. First, the foundation of all runways, taxiways, and airside pavements is soil, which is not a homogenous material. Not only does it vary widely from place to place, but it also varies with time and/or as a function of the weather. Although soils have been classified into a limited number of groups, variability within each group prevents soil classification from providing a complete answer for defining properties of interest to the flotation analyst. A second source of flotation's varied nature stems from the diverse method used by different agencies and countries in solving their particular problems with the materials they have at hand. Third, the economics involved dictates, and will continue to dictate, differences in methods applicable to a given pavement construction. Fourth, and finally, the military is particularly interested in operation on semi-prepared and unpaved areas, such as mats, membranes, and unsurfaced soil. Although technology has not produced a uniform methodology, efforts have been applied in this direction on an international scale. While the product of these efforts cannot provide a total focus in the foreseeable future, a uniform method of reporting aircraft flotation has been adopted with good success. This method, termed Aircraft Classification Number/Pavement Classification Number (ACN/PCN), is supported around the world as a result of its promulgation by the International Civil Aviation Organization (ICAO) as a single airfield weight-bearing reporting method. ACN/PCN was devised for conventional flexible and rigid pavements and was not made applicable to mat, membrane, and unsurfaced soil landing fields. In order to update this successful reporting method to take into account more modern pavement analysis approaches, the ICAO is introducing a replacement method, the ACR/PCR system. Flotation analysis will continue to be concerned with the broad array of methods for design, evaluation, and weight bearing reporting of pavements and rapidly prepared unpaved landing areas. With the above in mind, the purpose of this document is to inform the aircraft flotation analyst of the various methods likely to be used and to characterize them for evaluating the capability of aircraft to operate on airport runways, taxiways, and airside pavements.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

Aircraft Ground Flotation Analysis Methods, ARP1821, Revision B, April 2016.

Landing Area/Landing Gear Compatibility - A Brief History of SAE/Corps of Engineers Cooperation, AIR4243, Revision A, December 2014.

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass, D2216, March 2019.

Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, D4318, June 2017.

Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils, D1883, December 2021.

Standard Test Method for CBR (California Bearing Ratio) of Soils in Place, D4429, February 2018.

2.1.3 U.S. Department of Defense Publications

Available from https://quicksearch.dla.mil/qsSearch.aspx.

MIL-STD-621, Subgrade, Subbase, and Test Method for Pavement Base-Course Materials, Revision A, CN2, December 1968.

2.1.4 Other Publications

(Accession numbers for procurement from Defense Documentation Center shown in parentheses at the end of reference where applicable.)

[1] Westergaard, H.M., “Stresses in Concrete Pavements Computed by Theoretical Analyses,” Public Roads, Vol. 7, No. 2, April 1926.

[2] Westergaard, H.M., “New Formulas for Stresses in Concrete Pavements of Air Fields,” Transactions of the American Society of Civil Engineers, Vol. 73, No. 5, New York, NY 10017, May 1947.

[3] Creech, D.E. and Gray, D.H., SEG-TR-67-52, Aircraft Ground Flotation Procedures - Paved Airfields, Aeronautical Systems Division, AFSC, Wright-Patterson AFB, OH 45433, April 1968.

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[10] Design of Concrete Airport Pavement, Portland Cement Association, Chicago, IL 60610, 1973.

[11] Pickett, G. and Ray, G.K., “Influence Charts for Concrete Pavements,” Transactions of the American Society of Civil Engineers, Vol. 116, New York, NY 10017, 1951.

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[14] Manual Series No. 11 (MS-11), Full-Depth Asphalt Pavements for Air Carrier Airports, Asphalt Institute, College Park, MD 20740, January 1973.

[15] Navy DM 21.3, Army TM 5-825.2, and Air Force AFM 88-6, Chapter 2, Flexible Pavement Design for Airfields, Departments of the Navy, the Army, and the Air Force, August 1978 (Tri-Service Design Manual).

[16] Witczak, M.W., Development of an All Bituminous Pavement Design Procedure for Naval Air Stations, Naval Facilities Engineering Command, Alexandria, VA 22332, July 1975.

[17] Barker, W.R. and Brabston, W.N., Development of a Structural Design Procedure for Rigid Airport Pavements, TR S-75-17 (FAA-RD-74-199), U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS 39180, September 1975.

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[19] TM 5-825-3-1/AFM 88-6, Chap. 2, Section A. "Flexible Pavement Design for Airfields (Elastic Layered Method), Department of the Army and Air Force, November 1989.

[20] TM 5-825-3-1/AFM 88-6, Chap. 3, Section A. Rigid Pavement Design for Airfields (Elastic Layered Method), Departments of the Army and Airforce, September 1988.

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3. FLOTATION ANALYSIS FEATURES AND DEFINITIONS

In order for the aircraft designer to ensure that satisfactory flotation characteristics are incorporated in an aircraft, one or more of the many available specialized analytical methods must be applied. Since the problem involves the interaction of the aircraft and the runway, analysis methods developed over the years require use of both aircraft and runway characteristics. Therefore, this section includes brief descriptions of pertinent aircraft and airfield parameters, and also serves to introduce the degree of specialization of the analytical methods which are discussed in Section 4.

3.1 Flotation Definition

Aircraft flotation is a measure of an aircraft's ability to operate over an airfield surface without applying an unduly severe loading to the airfield surface. The surface may be paved or unpaved and includes both runway and taxiway areas. In general, lower tire loads and/or lower tire pressures induces less stress on the various layers of runway surfaces, thereby increasing flotation capability. Increasing the number of tires on gears can also increase flotation capability when a specific flotation capability is a desired operational requirement.

3.2 Aircraft Flotation Parameters

Aircraft parameters which are pertinent to its flotation characteristics, and which typically are inputs to the analytical methods discussed in Section 4, include wheel load, tire contact area or pressure, and tire footprint spacing. Tire inflation pressure relates the wheel load and tire contact area. Two types of wheel loads are considered, as applicable. For landing gear with one wheel the applied load is termed single wheel load (SWL). For multi-wheel landing gear, the term equivalent single wheel load (ESWL) has assumed a decisive role in reflecting the cumulative effect of multiple wheel loads.

All early pavement design, and flotation methodology also, were concerned with single-wheel landing gear. With the advent of multiple-wheel landing gear, initially dual and dual-tandem wheel gear, the established single wheel design and flotation technology were extended to accommodate multiple-wheel loadings by establishing the concept of ESWL.

The conclusions of Technical Report AFWL-TR-70-113 [33], state: “based on the analysis, the principle of superposition is not valid, and stress-strain characteristics of the soil are nonlinear and dependent on stress level.” This conclusion, therefore, invalidates the concept of ESWL since ESWL is entirely dependent on the principle of superposition. Regardless, ESWL is still the dominant concept in pavement design and evaluation primarily because pavement designs based on this criteria have performed well and because currently, there is no technique that is clearly superior.

3.2.1 Definition of ESWL

ESWL is the load which, if applied to a single wheel would have the same effect on the runway as the particular multiple wheel arrangement being considered. Since the ESWL is a conceptual load on a single tire larger than the load on the one tire of the multiple wheel configuration it represents, and since load relates directly to pressure and tire contact area, it is necessary to arbitrarily select some aspect of the pressure-contact area relation in order to specifically evaluate ESWL for design or flotation. This can be – and has been – done in various ways, which should be understood to avoid misapplication of flotation concepts. The Army Corps of Engineers, waterways experiment station (WES), make use of the contact area of the one wheel of a multiple-wheel gear to define ESWL for flexible pavements. For load classification number (LCN) purposes discussed in 5.1.9, the British select the tire pressure of the multiple-wheels and let contact area increase to permit the determination of ESWL. Occasionally, a contact area is fixed without relation to the tires or the actual gear, or in relation to the area of all tires together.

3.2.2 ESWL in Relation to Pavement

A pavement structure consists of strong upper layers distributing the high intensity tire loads at the surface to the weaker lower layers. The way in which pavement strength requirements vary from surface to subgrade is substantially different for single-wheel than for multiple-wheel landing gear. Thus, a specific ESWL can be based directly on depth (thickness) of pavement structure for flexible pavement and indirectly on radius of relative stiffness (1) for rigid pavement. It follows that the ESWL for a particular multiple-wheel configuration and load will be quite different for pavements on high strength subgrade (thinner pavement, smaller radius of relative stiffness), than for pavements of low strength subgrade (thicker pavement, larger radius of relative stiffness).

3.2.3 Radius of Relative Stiffness

Radius of relative stiffness, which is a function of the concrete’s modulus of elasticity, thickness, Poisson’s ratio, and the modulus of subgrade reaction, relates the stiffness of a concrete slab to that of the subgrade. It is used in determination of ESWL for rigid pavement. Figure 1 illustrates the physical meaning of this quantity.

3.3 Airfield Runway Parameters

Runway parameters pertinent to the analysis of aircraft flotation are basically pavement thickness and strength of the support beneath. Treatment by pavement type is as follows:

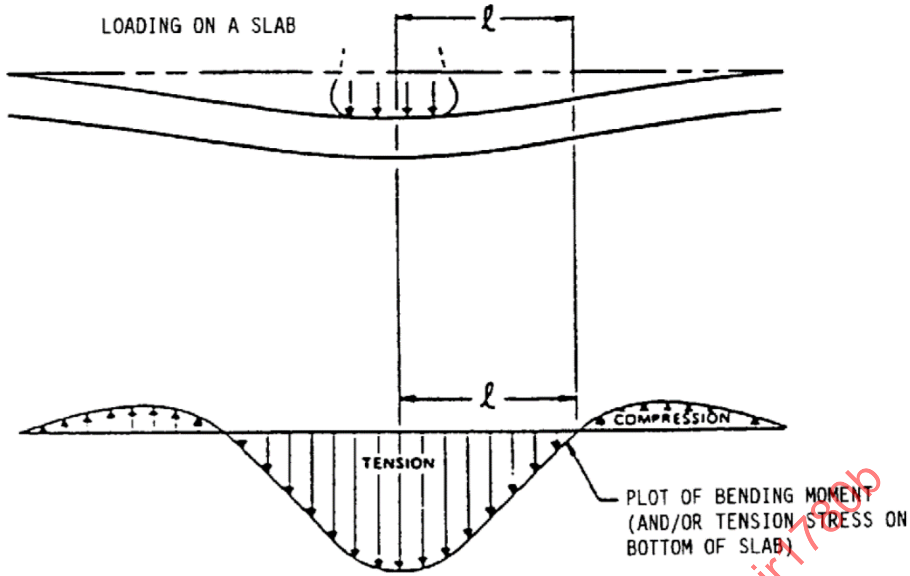


Figure 1 - Physical meaning of Westergaard's "radius of relative stiffness", ℓ

3.3.1 Paved Surface

Paved surfaces can be classified according to the method of their construction as either rigid or flexible in most instances. Regardless of such classification they are all concerned with the performance of the subgrade on which they are built. Portions of a given pavement are also classified according to the nature and frequency of loading to which they are exposed. For instance, portions such as runway ends which are subject to sustained loads require stronger pavement than the central portions of the runway which are momentarily loaded. The military groups pavements into traffic areas. An example for a typical layout for heavy load Air Force pavements is shown in Figure 2.

3.3.1.1 Rigid Pavements

Rigid pavements are all basically made of Portland Cement concrete. After initial construction they may be overlaid to increase their load bearing capability. The thickness of the pavement is the thickness of the concrete and does not include the thickness of any strengthening layers that may exist between the subgrade and the concrete. Common rigid pavement thicknesses are 8 to 14 inches (20 to 36 cm). Rigid pavements can be jointed, reinforced or nonreinforced, continuously reinforced, fibrous reinforced, or prestressed.

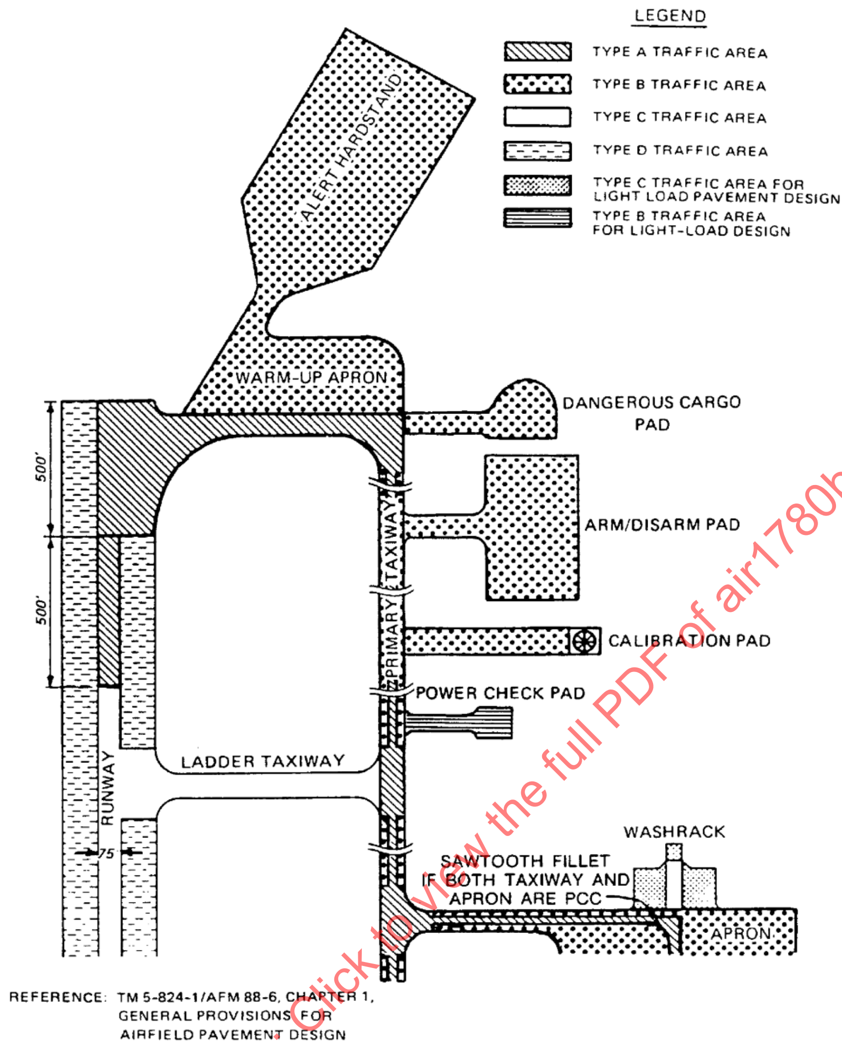


Figure 2 - Typical layout of Air Force heavy-load airfield

Pavement design considers three kinds of loading: interior, edge, and corner. Interior loading is that where the location of the load is remote from the edge of the slab. Loading across joints provides higher pavement moment, and therefore load transfer structure is frequently provided to transfer a portion of the edge load to the adjacent slab. Historically, design has been based on interior loading, considering that load transfer devices between adjacent edges cause the paved area to act as a continuous slab. In modern analysis, edge and corner loading are also considered.

Rigid pavement theory is historically based on the theories of Westergaard (references [1] and [2]) where the subgrade is assumed to act as a dense liquid. Several investigators have indicated that the subgrade probably behaves more as an elastic solid. Indeed, modern analysis methods now utilize a linear elastic method.

Although the Corps of Engineers prefers to measure the strength of rigid pavement in terms of its 90-day flexural strength, the modulus of rupture of concrete is often used. The range of modulus for design varies between 650 and 750 psi (4.48 and 5.17 MPa). This agrees with the nominal reported in reference [3], which also states that the minimum safety factors for critical areas and noncritical areas are 1.75 and 1.5, respectively. In some instances, these have been reported as low as 1.25 and as high as 2.0. Therefore, to allow for safety factors, the commonly used value for working stress is 400 psi (2.76 MPa).

3.3.1.2 Flexible Pavements

A flexible pavement is composed of one or more layers placed on a prepared subgrade and consists of a surface course of bituminous material (generally asphalt), a base course of treated or untreated granular material, and a subbase course of treated or untreated material. The complexity of their construction is illustrated in the schematic of Figure 3, which identifies the many layers that may be used. The total thickness of the pavement is usually considered the thickness above the subgrade. Common thicknesses of flexible pavements range from 8 to 60 inches (20 to 152 cm) or more. While not strictly a pavement, runways made of rolled gravel or crushed rock are used. For strength and flotation evaluation they are considered flexible pavements.

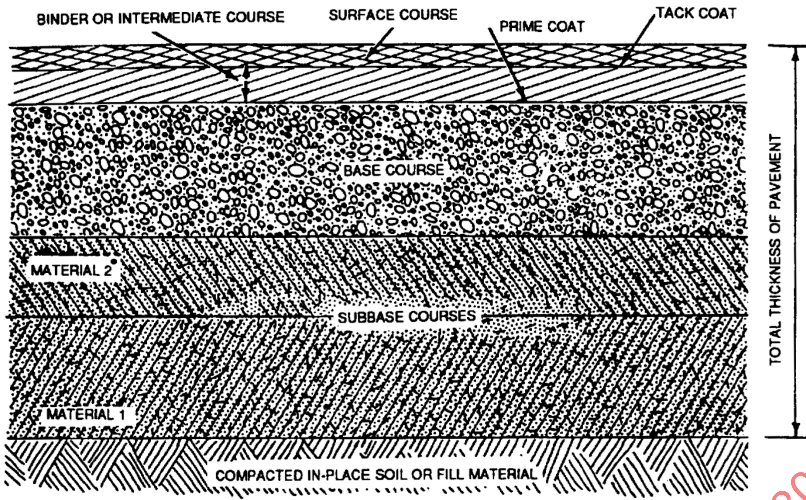
3.3.1.3 Other Pavements

Historically airfield pavements have been designed by a myriad of techniques, including many state highway methods. One that is unique was devised by the Port Authority of New York and New Jersey for use at airports under their control. The principal structure layer in the pavement is made of lime, cement, and flyash (L-C-F) mixed with sand.

Soil stabilization can be used to improve the load carrying capability and durability characteristics of soil through the use of admixtures such as cement, lime, bitumens, L-C-F, or a combination of these. Note that the term soil stabilization should not be confused with soil modification, which is used by the Corps of Engineers. For modification, additives are applied to improve the soil characteristics sufficiently to provide a working platform for airfield construction. In the case of soil stabilization credit is given for increase in strength, whereas it is not for soil modification.

3.3.1.4 Overlays

Overlays of concrete or asphalt are used to serve one or more purposes, such as extending the pavement service life, improving the surface topology, restoring the surface friction, or strengthening the pavement. Overlays are most commonly flexible; but rigid overlays on rigid pavements are used, and rigid overlays of flexible pavements are sometimes employed.



*Material 2 is of a higher quality than material 1.

PAVEMENT	Combination of subbase, base, and surface constructed on subgrade
SURFACE COURSE	A hot mixed bituminous concrete designed as a structural member with weather and abrasion resisting properties. May consist of wearing and intermediate courses.
PRIME COAT	Application of a low viscosity liquid bitumen to the surface of the base course. The prime penetrates into the base and helps bind it to the overlying bituminous course
SEAL COAT	A thin bituminous surface treatment containing aggregate used to waterproof and improve the texture of the surface course
COMPACTED SUBGRADE	Upper part of the subgrade which is compacted to a density greater than the soil below
TACK COAT	A light application of liquid or emulsified bitumen on an existing paved surface to provide a bond with the superimposed bituminous course
SUBGRADE	Natural in-place soil, or fill material

Figure 3 - Typical flexible pavement and terminology

3.3.2 Subgrade Strength

Subgrade strength is commonly defined by either the Modulus of Subgrade Soil or Soil Reaction or California Bearing Ratio (CBR). The modulus of subgrade reaction, *k*, is defined as the applied load in pounds per square inch divided by the soil deflection in inches. Thus, *k* has the dimensions of pounds per inch cubed, values usually considered varying from 50 to 500 (13.6 to 135.7 MN/m^3). Base course materials are often placed over natural subgrade to improve the overall *k* value, which is typically associated with rigid pavement strength estimation. The CBR of the soil or subgrade is measured by either laboratory or field tests employing a standard loading device forcing a plunger into the soil. CBR is the load expressed as a percentage of the load required to obtain the same penetration in a standard, compacted, crushed-stone sample. The range of CBR usually considered is from 4, which will support airfield construction equipment, to 100. CBR is the strength parameter typically associated with flexible pavements and unpaved soil airfields. Procedures for determining modulus of subgrade reaction and CBR are described in reference [4]. An approximate correlation between *k* and CBR is shown in Figure 4.

The military may also use more expediently determined parameters, namely cone index and airfield index. These are obtained by measuring the resistance to penetration of a cone by the soil. The latter is especially adaptable for troops in the field. Their approximate correlation with CBR is shown in Figure 5.

3.3.3 Unpaved Surfaces

Unpaved surfaces make up a category of runways and taxiways ranging from natural, unprepared, bare soil or turf to surfaces covered with metal mats or synthetic membranes. The strength of the soil for unpaved surfaces is typically expressed in terms of CBR.

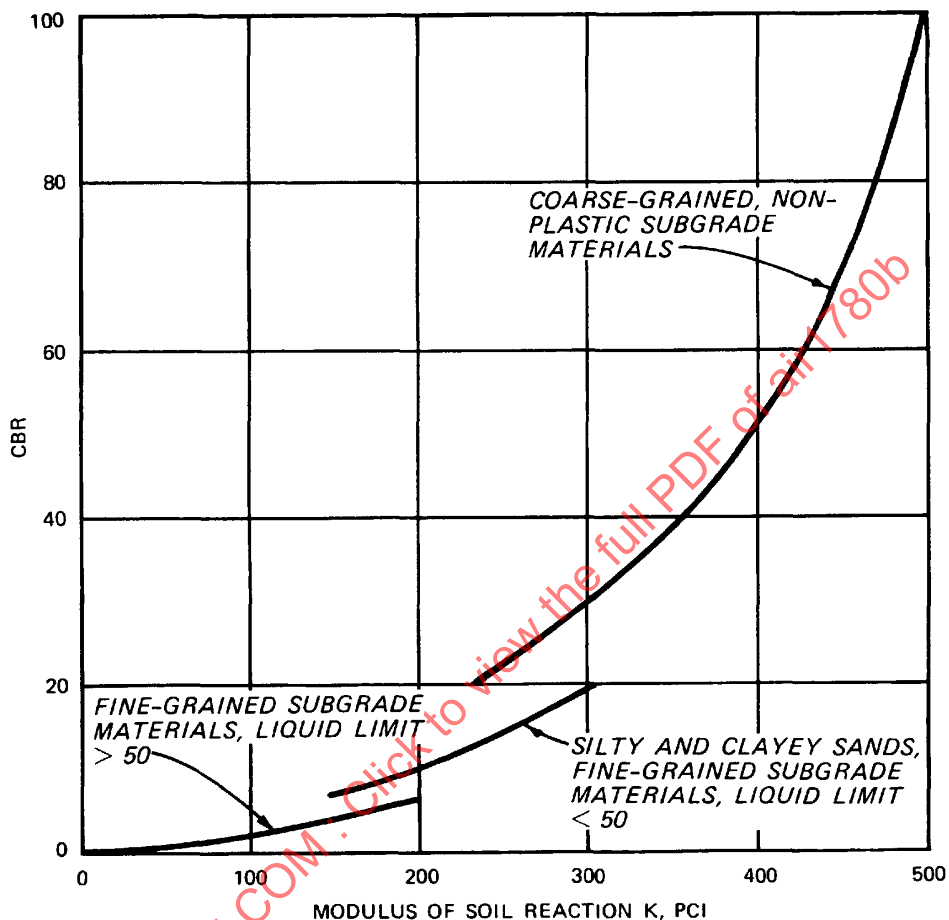


Figure 4 - Approximate inter-relationship of bearing values

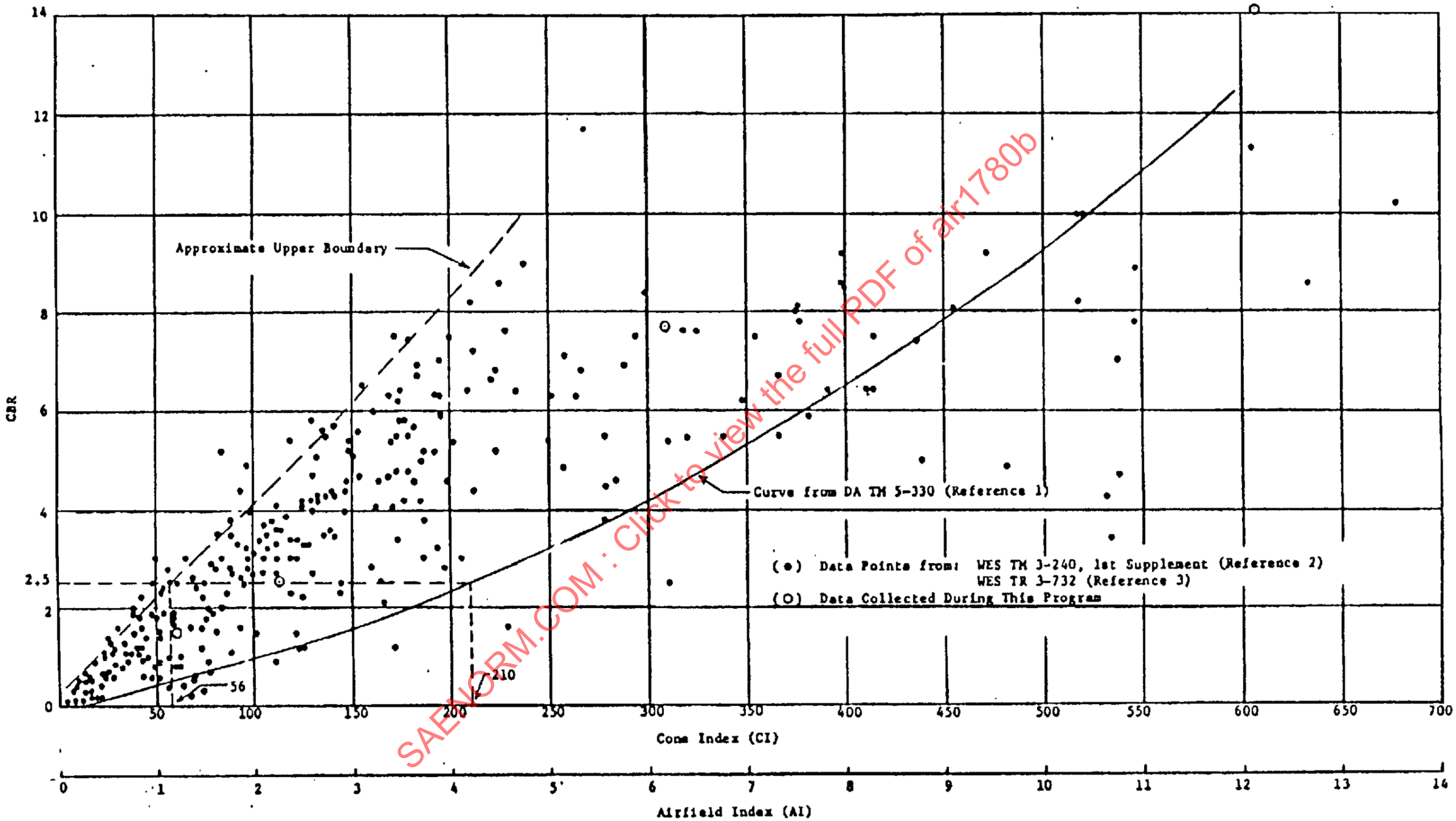


Figure 5 - Correlation of CBR, CI, and AI (fine-grained soils)

3.4 Glossary of Terminology Used in Analysis of Flotation

This glossary is adapted from ESL-TR-86-39, reference [5].

AIRFIELD INDEX: An index of soil-shearing resistance obtained using an airfield penetrometer. See Airfield Penetrometer definition in this glossary.

AIRFIELD PENETROMETER: A probe-type instrument designed to measure soil strength. It consists of a 30 degree right circular cone with a base diameter of approximately 1/2 inch (12.7 mm), 0.2 square inch (129 mm^2) end area mounted on a graduated staff; on the opposite end of the staff are a spring, a load indicator, and a handle. The overall length of the assembled penetrometer is about 36-1/8 inches (91.8 cm).

AUTOMATED CONE PENETROMETER: A truck-mounted automated system for making trafficability penetrometer measurements of soil strength. A servo hydraulic cylinder is used to apply force through a shaft to a standard trafficability cone (with a 0.5 square inch (323 mm^2) end areas and an approximate 0.8 inch (2 cm) diameter) maintaining a constant 1.25 in/s (3.2 cm/s) rate of penetration into a soil surface. The force applied (penetration resistance) is continuously measured and automatically printed out on paper tape for each 2 inches (50.8 mm) of cone penetration to a maximum 16 inch (40.6 cm) depth. The ACP permits more accurate and faster trafficability penetrometer measurements than can be obtained manually with the standard trafficability penetrometer.

CALIFORNIA BEARING RATIO: A widely used index to express soil strength is for use with empirical procedures for the design of unsurfaced, expediently surfaced, and flexible airfield surfaces. The CBR test is essentially a penetration test (using a 2 square inch (12.9 cm^2) steel rod) that measures penetration resistance in pounds force at 0.1 inch (2.54 mm) penetration or 0.2 inch (5.08 mm) penetration if larger. The CBR value is expressed as a percentage of a standard penetration if larger. The CBR value is expressed as a percentage of a standard penetration value for crushed stone. MIL-STD-621 provided the detailed CBR test procedure but is now canceled. ASTM D4429 now provides the industry standard field test for CBR while ASTM D1883 provides a laboratory test for CBR. Considerable time is required to perform a CBR test, normally 2 to 3 hours. Therefore, the method is impractical for rapidly evaluating airfield soil strength.

COHESIONLESS SOIL: A sand soil not having any significant fines as glue-like binder for the sand grains.

COHESIVE SOIL: A clay soil, loam, or sandy soil having glue-like fines as binder for the sand grains.

CONE INDEX: An index of soil-shearing resistance obtained using a trafficability cone penetrometer. See trafficability cone penetrometer definition.

CONE PENETROMETER: A probe-type instrument designed to measure soil strength, consisting of a shaft attached to the base of a right circular cone. The cone is driven into the soil by applying force to the shaft. For soil airfield strength measurements, three different penetrometers have normally been used. These are the automated cone penetrometer, and two manually operated cone penetrometers, the trafficability and airfield cone penetrometers. Each of these penetrometers is defined in this glossary.

FOOTPRINT: The tire area in contact with the ground surface. A bias ply tire in equilibrium on a flat, rigid surface generates a nominally elliptical footprint which can be defined in terms of width and length as a function of load applied to the tire type, size, contained air pressure, and deflection. The area within this ellipse is the gross footprint area used as input to most techniques for predicting aircraft operation on ground surfaces. The actual area of tread within the ellipse which is in contact with the surface is the net footprint area. The net footprint area is sometimes used as input to more detailed tire and tire/surface analysis. Usually, footprint area means gross footprint area, and tire contact area means the same as gross footprint area. Radial ply tires exhibit a more rectangular footprint when in equilibrium on a flat, rigid surface. In general, most flotation analyses utilize the footprint area with some approximation (sometimes circular) for the footprint area.

SINKAGE: The distance between the undisturbed soil surface and the bottom of the tire.

LIQUID LIMIT: The moisture content of fine-grained soil (or the fine-grained portion of a coarse-grained soil) when it passes from the liquid state to the plastic state. It is the boundary moisture condition between the state at which the soil flows under its own weight and the state at which it can be remolded without crumbling. A detailed explanation is provided in ASTM D423.

MILITARY GROUND VEHICLE RUT DEPTH CORRELATION: A technique for rapidly determining the soil strength of unprepared and/or semi prepared soil airfields by using U.S. Army Engineers Waterways Experiment Station-developed dimensionless ground mobility parameters to correlate rut depths developed from standard military ground vehicles to soil strength. Standard military ground vehicles (reference [6]) such as M151 (1/4-ton), M37 (3/4-ton), M34 (2-1/2-ton) or M55 (5-ton) are initially driven across the soil airfield site and observations of the resulting rut depth (from rear tire) are made as to depth of rut (in inches) and location. With this information, a correlation chart can then be used to determine the suitability of the soil strength at that site to support at least one pass of certain military aircraft.

MOISTURE CONTENT: The amount of water in a given soil sample. Specifically, it is the weight of water in soil divided by the weight of the solid mineral grains. A detailed explanation is provided in ASTM D2216.

PLASTIC LIMIT: The moisture content at which a fine-grained soil passes into the plastic state from the semisolid state or vice-versa. A detailed explanation is provided in ASTM D4318.

PLASTICITY INDEX: The difference between liquid limit and plastic limit. It is a primary indicator of soil behavior.

RUT DEPTH: The distance between the original ground surface and rut-bottom elevations after a tire has passed over the surface and all rebound has been completed.

TIRE DEFLECTION (Vertical/Radial): The difference between loaded and unloaded tire section heights, where tire section height is the distance between the wheel bead seat and the tire tread against a rigid surface. Often the term tire deflection is used to mean percent tire deflection. The percent tire deflection is equal to the tire deflection divided by the tire free height (unloaded section height above the top of the wheel rim flange) multiplied by 100.

TIRE SLIP (Expressed as a Percent): The difference between aircraft velocity and tire tread velocity divided by aircraft velocity. Zero tire slip indicates a fully free-rolling wheel, and 100% slip indicates fully locked wheel (no rotation).

TRAFFICABILITY CONE PENETROMETER: The trafficability cone penetrometer is a probe-type instrument designed to measure soil strength. It consists of a right circular cone with a 0.5 square inch (323 mm^2) base area and is operated at a penetration rate of approximately 1.25 in/s (31.8 mm/s).

TURN ANGLE: The angle between the plane of the tire and the velocity vector at the vertical axis of the wheel (also called the slip angle, tire yaw angle, or tire cornering angle).

3.4.1 Glossary of Terms for Traffic on Airfield Pavement

Parameters based on the use of an airfield have been developed to address the performance of airfield pavements. There are several terms related to aircraft traffic on pavement that have been used in airfield design. Among these are cycles of operation, aircraft passes, annual departures, takeoffs, and landings, and so on.

AIRCRAFT PASS: The movement of an aircraft across a given pavement is considered one aircraft pass. In practice, the Air Force considers that a takeoff and a landing constitute one pass per their paved surface method. In effect, they consider a takeoff and a landing two passes per their unsurfaced method. The technique for determining pass to coverage ratio by either method is identical.

ANNUAL DEPARTURES: The number of aircraft takeoffs at an airfield in a year’s time. For the purpose of developing design criteria, a departure is considered to be one pass. The effect on the pavement of the lighter weight landing is neglected.

COVERAGE: The computational technique used to develop design criteria for the military and FAA requires that passes be converted to coverages (reference [7]). A coverage for a flexible pavement is defined as the application of a sufficient number of wheel loads to completely cover the pavement surface within the traffic lane one time. A coverage for rigid pavement is the application of a sufficient number of wheel loads such that each point of the pavement surface within the traffic lane has received one maximum stress repetition. The traffic lane is that width of pavement which is exposed to 75% of the traffic. It is equal to the sum of the center-to center spacing of the two outermost tires on the aircraft plus one tire footprint width plus wander. Wander is defined as the maximum lateral movement of a point on the centerline of the aircraft about the centerline on taxiways and runways during operation of the aircraft.

OTHER CRITERIA: The PCA design method makes use of a safety factor for including the effects of traffic or applies a detailed analysis of fatigue effects using a load repetition factor similar to coverages used above. The Asphalt Institute, as do many other procedures, requires that the number of aircraft repetitions be an input to the design criteria.

The Load Classification Number method (reference [8]) devised in the United Kingdom (and remaining relevant for UK military aircraft) also recognizes fatigue in terms of movements. A movement is assumed to be either a takeoff or a landing. Table 1 defines the number of allowable movements as a function of the ratio of the aircraft LCN to the airfield LCN. Note that these ratios are applicable to the Load Classification Number method only and not to the Load Classification Group method. See 5.1.9 for an explanation of LCG and LCN.

Table 1 - LCN for limited pavement use

Ratio of Aircraft LCN / Pavement LCN	Aircraft Passes	Remarks
Up to 1.1	Unlimited	
From 1.10 to 1.25	3000	Entails acceptance of some minor failures.
From 1.25 to 1.50	300	Some cracking may occur in concrete and possibly local failure in flexible surfaces.
From 1.5 to 2.0	Very Limited	Permission given only after examination of pavement and test data.
Greater than 2.0	Emergency	

Two categories of traffic are identified, channelized for taxiways and nonchannelized for runways. The pass to coverage ratios (P/C) for various landing gear types for these categories are found in Table 2 (see reference [9]).

Table 2 - Channelized and non-channelized P/C in the United Kingdom

Gear Configuration	Pass[1] to Coverage Ratio Channelized	Pass[1] to Coverage Ratio Nonchannelized
Large aircraft, e.g., C-5 and 747	2.00	2.75
Dual tandem gear	2.25	4.00
Dual gears	5.00	10.00
Single wheel gears	10.00	20.00

[1] A pass is considered to be a takeoff and a landing.

4. AIRCRAFT FLOTATION METHODOLOGY

In some cases, an aircraft flotation methodology may be very closely related to a runway design method. However, the context in which each method below is discussed is that of aircraft flotation analysis. It is noted that while flotation involves the operation of aircraft on runways, which implies dynamic loading, most analysis methods make use of static loads.

4.1 Paved Surface Methods

Two fundamental types of paved surfaces are in use, rigid and flexible. Rigid pavements are pavements constructed from concrete, reinforced concrete, or a similar material that forms a slab, which resists the applied loads in bending. Rigid pavements can be applied directly on graded soil, provided the material has an appropriate resistance. As some soil materials suffer from ‘pumping’, where repeated loadings can displace the material under the pavement, a compacted subgrade is employed to support the pavement. A flexible pavement, unlike a rigid pavement, does not have significant strength in bending. Loads applied to the pavement are transmitted to the base course beneath; the pavement resists the shear forces imparted by the contact pressure and distributes the stresses into the lower layers in such a way that they do not exceed the strength of the pavement layers or subgrade.

The development of paved surfaces is an ongoing civil engineering topic. New materials and processes are constantly being developed to improve the bearing capacity of runways, taxiways, and aprons. As each new material and technique may require its own type of design analysis, the determination of the compatibility between the paved surface and aircraft can be complicated. In order to avoid the chaos that would result from each airport operator prescribing limitation rules unique to its runways, the aircraft industry has adopted a number of standardized rating systems to provide a means of assessing aircraft and ground surface compatibility. These methods, requiring international agreement, arise only periodically. The LCN, ACN, and ACR systems were developed to provide a universal assessment and reporting baseline for aircraft landing gear loading characteristics, while pavement development and assessment progresses in parallel. The standardized reporting systems rely on accepted pavement design methods (even if a specific runway was designed using a different method). The most modern pavement design methods utilized layered elastic theory and finite element analysis while most earlier methods used CBR methods for flexible pavement design and Westergaard's theory for rigid pavement design (these are outlined in Section 5). To aid in understanding, the principal pavement design methodologies are outlined below before detailing the reporting methods. Historical methods for pavement design (especially flexible pavement design) were largely empirical and used empirical means and correction factors to ensure an appropriate design life. Modern methods follow a rational approach similar to that used for the design and analysis of metals: stress analysis of the pavement is performed and the life is computed based on empirically determined material fatigue curves. The separation of the analysis into a clear stress calculation phase and a clear fatigue life computation phase permits the stresses arising from multiple wheels and multiple wheels in tandem to be directly, and more accurately, assessed. This type of analysis procedure is called a 'mechanistic-empirical' approach. The move to a rational approach for the determination of capability of the pavement allows pavement engineers to predict performance based on the strength properties of the materials utilized, rather than having to repeat many empirical life tests for every new paving innovation [35].

4.1.1 Pavement Design Analysis – Layered Elastic and Finite Element Analysis

Current pavement design procedures for rigid and flexible surfaces use a layered elastic representation of the pavement courses and supporting surfaces as shown in Figure 6. Each layer is considered as a homogenous elastic solid with its own thickness, elastic modulus, and Poisson's ratio.

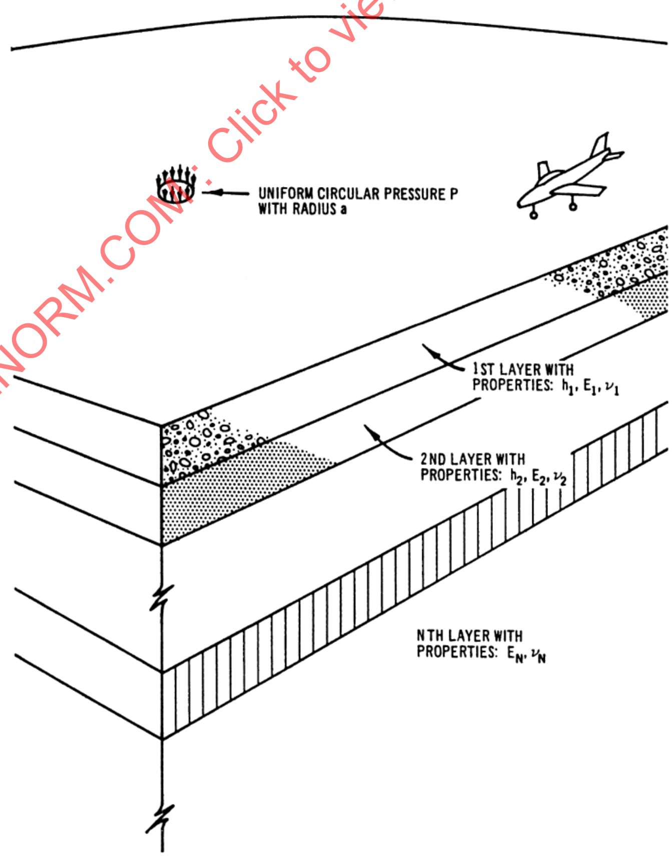


Figure 6 - Multi-layered linear elastic representation

Burmister developed closed form solutions to the layered elastic problem for two layer [36] and three layer [37] representations. Modern approaches utilize computer simulations to solve for an unrestricted number of layers. These approaches can be a variation of the Burmister approach, typically applied for flexible pavements, or can be solutions using finite element methods (usually applied for rigid pavements). Two example finite element calculation results are shown in Figure 7. The left hand image shows the distribution of bending stress in a rigid pavement slab loaded by a six-wheel bogie main landing gear; six well-defined stress peaks corresponding to the six tires of the landing gear are evident. The pavement slab adjacent to the tire footprint is not shown in order to expose the edge of the loaded slab; tensile stresses on the bottom of the slab and compressive stresses on the top are clearly evident. The right hand image shows the deflection basin computed for a four wheel main landing gear where the tire footprint is loading the edge of the concrete slab. In this simulation the bottom layer of elements has an infinite formulation, simulating the response of an infinitely deep elastic subgrade.

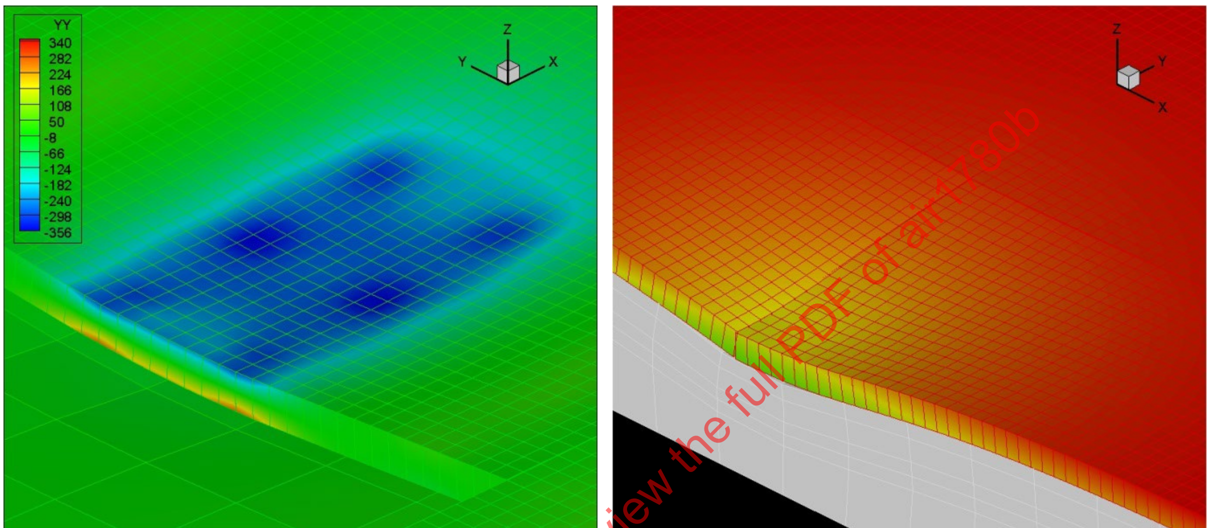


Figure 7 - Finite element analyses of rigid pavements. Left: Stress in a slab loaded by a six wheel bogie gear; Right: Deflection of slab loaded by a four wheel bogie gear

For flexible pavements, the subgrade modulus (if not known) can be estimated by the expression:

$$E_{SG} = 1500CBR$$

Where the modulus of elasticity is in pounds per square inch. For rigid pavement design, the foundation modulus of elasticity, E_{SG} (if not known) can be estimated based on the modulus of subgrade reaction, *k*:

$$E_{SG} = 20.15k^{1.284}$$

Where E_{SG} is in pounds per square inch and *k* is in pounds per cubic inch [38].

The process of determining the appropriate pavement thickness relies on using the layered elastic/finite element analysis to determine the stresses in the pavement and subgrade layers. Depending on the aircraft expected to use the pavement, the arrangement of the landing gears, and an assumption for the distribution of traffic (wander), a stress history for a proposed (or actual) pavement can be developed. This stress history can include the direct load impulse resulting from tires that pass the same point sequentially, eliminating the need to utilize correction factors which estimate this effect. The stress history is then used with an empirically derived failure model to determine the expected life. Additional considerations such as pavement temperature and frost resistance also form part of the complete pavement design process.

The life of the pavement is expressed using the ‘Cumulative Damage Factor’ (CDF). It represents the fraction of the structural fatigue life of a pavement which has been consumed and it is expressed as the ratio of applied load repetitions to allowable load repetitions to failure, or, for one airplane and constant annual departures:

$$CDF = \frac{number\ of\ applied\ load\ repetitions}{number\ of\ allowable\ repititions\ to\ failure}$$

$$= \frac{(annual\ departures) \times (life\ in\ years)}{\left(\frac{pass}{coverage} ratio\right) \times (coverages\ to\ failure)} = \frac{applied\ coverages}{coverages\ to\ failure}$$

When CDF = 1, the pavement will have used up all its fatigue life.

When CDF < 1, the pavement will have some life remaining, and the value of CDF will give the fraction of the life used.

When CDF > 1, all the fatigue life will have been used up and the pavement will have failed.

The definition of failure which is employed is a particular structural failure mode according to the assumptions and definitions on which the design procedures are based. A value of CDF greater than one does not necessarily mean that the pavement will no longer support traffic, but that it will have failed according to the definition of failure used in the design procedure (and within the constraints of uncertainties in material property assumptions, etc.) Notwithstanding the potential variation in the type of failure mode, the pavement thickness design is based on the assumption that failure occurs when CDF is equal to unity. The damage done to the pavement from different aircraft types is accounted for by using Miner's linear damage accumulation rule, where:

$$CDF = CDF_1 + CDF_2 + \cdots + CDF_{n-1} + CDF_n$$

Many analysis tools compute a separate CDF for each failure mode included in the design procedure. For example, in flexible pavement design, a CDF is likely to be calculated for the asphalt as well as the subgrade; failure of the pavement is driven by the highest CDF in the structure.

The effect of aircraft wander is addressed explicitly in linear elastic and finite element approaches. In the FAA pavement design software FAARFIELD, CDF is calculated for each 254 mm (10 inch) wide strip along the pavement over a total width of 20.8 m (68.2 feet). Pass-to-coverage ratio is computed for each strip based on a normally distributed airplane wander pattern with standard deviation of 775 mm (30.5 inches), equivalent to airplane operation on a taxiway. A CDF is calculated for all resulting 82 strips, with the maximum resulting CDF being the value considered for design. Even with the same gear geometry, aircraft with different main gear track widths will have different pass to coverage ratios in each of the 254 mm strips and may show little cumulative effect on the maximum CDF.

The damage model used depends on the design code and the country where the pavement is designed. For pavements in the USA, Advisory Circular 150/5320-6 specifies the use of the FAARFIELD tool. Other countries have similar but subtly different methods and tools. France requires the use of the ALIZE tool while Australia specifies the use of the ASPDS code. A description of the failure models used in FAARFIELD are provided as they are indicative of the methodology used in most codes.

For flexible pavement design in FAARFIELD, the maximum vertical strain at the top the subgrade and the maximum horizontal strain at the bottom of all asphalt layers are the design criteria. The subgrade failure model used to find the number of coverages to failure for a given vertical strain at the top of the subgrade is:

$$\log C = \left(\frac{1}{-0.1638 + 185.19\varepsilon_v}\right)^{0.60586}, \text{ for C > 1000 coverages, and}$$

$$C = \left(\frac{0.004141}{\varepsilon_v}\right)^{8.1}, \text{ for C ≤ 1000 coverages}$$

where:

C = number of coverages to failure

ε_v = vertical strain at the top of the subgrade

For asphalt fatigue, the failure model is based on the concept that the number of coverages to failure is determined by a quantity called Ratio of Dissipated Energy Change (RDEC) [39]. In a large number of asphalt beam fatigue tests it has been found that the Plateau Value (*PV*) of RDEC is a reliable predictor of the number of cycles to fatigue failure (N_f). For a broad range of asphalt mixes, this relationship is given by:

$$N_f = 0.4801(PV)^{-0.9007}$$

For a given horizontal strain at the bottom of the asphalt layer, the value of RDEC can be estimated by:

$$PV = 44.422\varepsilon_h^{5.14}S^{2.993}(GP)^{-0.4063}$$

where:

PV = estimated value of the RDEC plateau value (dimensionless)

S = hot mix asphalt initial flexural stiffness, in psi; this is not the same as the modulus, *E*, used to compute strain in the layered elastic analysis

ε_h = horizontal strain at the bottom of the asphalt layer

VP = volumetric parameter: $VP = \frac{V_a}{V_a+V_b}$

V_a = volume of air voids

V_b = asphalt content by volume

GP = gradation parameter: $GP = \frac{P_{NMS}-P_{PCS}}{P_{200}}$

P_{NMS} = percentage of aggregate passing the nominal maximum size sieve

P_{PCS} = percentage of aggregate passing the primary control sieve

P_{200} = percentage of aggregate passing the #200 (0.075 mm) sieve

Default values of these parameters are assigned in FAARFIELD to represent typical hot mix asphalt (P-401) mixtures. The values are: S = 600000 psi; V_a = 3.5%; V_b = 12.0%; P_{NMS} = 95%; P_{PCS} = 58%; P_{200} = 4.5%.

For rigid pavement design in FAARFIELD, the CDF is calculated using the larger of the horizontal edge stress at the bottom of the concrete layer, or the horizontal interior slab stress. To account for load transfer to adjacent slabs, the free edge stress is computed for the gear load and reduced by 25%. For gear loading along the slab edge, it is necessary consider the orientation of the landing gear. The general procedure is take the higher of the edge stress with the gear oriented parallel to the slab edge and the edge stress with the gear oriented perpendicular to the slab edge. Edge stresses for rigid pavements are computed using the three-dimensional finite element model. Interior stresses are computed using the layered elastic model. The interior stress is assumed to be 95% of the maximum horizontal stress computed by the layered elastic calculation. The rigid pavement failure model used in FAARFIELD has the general form:

$$\frac{DF}{F_{CAL}} = \left[\frac{F_s'bd}{\left(1-\frac{SCI}{100}\right)(d-b)+F_s'b}\right]\log C + \left[\frac{\left(1-\frac{SCI}{100}\right)(ad-bc)+F_s'bc}{\left(1-\frac{SCI}{100}\right)(d-b)+F_s'b}\right]$$

where:

SCI = Structural Condition Index, an indicator of the condition of the pavement where 100 is fully structurally sound. An SCI of 80 is the FAA definition of structural failure of a rigid pavement and is consistent with 50% of slabs in the traffic area exhibiting a structural crack.

DF = design factor; it is defined as *R/σ*, where *R* is the concrete flexural strength and *σ* is the computed concrete tensile stress

F_{CAL} = stress calibration factor; F_{CAL} = 1.0 for FAARFIELD

F_S' = stabilized base compensation factor; the failure model above assumes that the SCI deteriorates under traffic as a linear function of the logarithm of coverages (after first reaching the first structural crack). The factor F_S' is used to adjust the slope of the line when the structure includes a higher quality (stabilized) base. When the concrete slab is placed on an 8-inch thick crushed aggregate (P-209) layer, or on a 4-inch thick stabilized layer (500000 psi), the value of F_S' is one and the basic (uncompensated) failure model is recovered. But if the thickness or quality of the base/subbase structure is greater than either of these two conditions, F_S' decreases, and the number of coverages to failure increases. Adjusting the slope of the line in this way recognizes that a concrete slab placed on a stabilized base will not deteriorate as rapidly following the appearance of a first crack compared to a similar slab on a conventional (aggregate) base.

a, *b*, *c*, and *d* = parameters whose value depends on the subgrade modulus. Parameters used in FAARFIELD were obtained by analyzing failures of full-scale rigid pavement test pavements at the National Airport Pavement Test Facility (NAPTF), as well as previous full-scale tests. In such failure data there is inherently a considerable amount of scatter. Lines were drawn encompassing 50% and 85% of the failure points, from which the following parameters were obtained:

Parameter	50% Failure Envelope	85% Failure Envelope
a	0.760	1.027
b	0.160	0.160
c	0.857	1.100
d	0.160	0.160

The values of *a* and *c* transition linearly from the 50% values for low strength subgrades represented by *E* = 4500 psi (approximately CBR 3), to the 85% values for higher strength subgrades represented by *E* = 15000 psi (approximately CBR 10). This transition reflects the fact that thinner concrete pavements on strong foundations are more likely to experience top-down cracking (e.g., corner breaks) than pavements on weaker foundations. Since the top-down cracking failure mode is not considered in FAARFIELD design, the use of the more conservative 85% failure curve is justified for higher subgrade strengths.

Failure for a rigid pavement in FAARFIELD is defined as *SCI*= 80. For a new rigid pavement, the program iterates on the thickness of the concrete layer (the design layer) until the failure model predicts a value of *SCI*=80 at the end of the design life (20 years for standard designs). The number of coverages to failure (*C*) is therefore the number of coverages for *SCI* = 80 at any given value of *R/σ*.

4.1.2 Aerospace Industries Association (AIA)

Strictly speaking, the AIA has not provided a method of its own for flotation analysis but specifies methods to be used for defining flotation of commercial aircraft used by its members. Recognizing the need to standardize the characteristics of airplanes for airport planning, it published NAS 3601 (reference [21]).

NAS3601 requires use of the ACN-PCN System for reporting aircraft weight bearing limits for pavements. NAS3601 also defines the other data to be presented in "Airplane Characteristics for Airport Planning" and it is common practice for NAS3601 to be used for all commercial and civil aircraft. It was anticipated that NAS3601 would have been updated to require ACR-PCR reporting, but that standard has been canceled as of September 2021. Nevertheless, it is anticipated that aircraft manufacturers will continue to produce airport planning documents and that they will continue to include pavement loading guidance, incorporating ACR-PCR and ACN-PCN until the complete international adoption of ACR-PCR.

Probably all commercial aircraft flotation reporting, at least in the United States, has been done per the dictates of NAS 3601 since its publication in 1968.

4.1.3 Airplane Classification Rating/Pavement Classification Rating (ACR/PCR)

A new international standard for paved runway strength reporting and aircraft capability reporting has been developed, to take into account the refined analysis permitted by finite element methods and the layered elastic mechanistic approach. The ICAO ratified the move to the ACR/PCR system in 2020 with full international adoption expected by 2024. The FAA promulgates this requirement in Reference [44] and [45]. This change is to take advantage of current methods of mechanistic pavement analysis (as outlined in 4.1.1) and to eliminate the need for various empirical factors (such as alpha factors) that are a fundamental part of the analyses which underpin the ACN/PCN method. The replacement methodology is termed the ACR/PCR (Aircraft Classification Rating/Pavement Classification Rating) system. The system adopts the same concepts as the ACN/PCN method (namely, that an aircraft with an ACR less than the declared PCR may operate without restriction on that surface) and a similar reporting format. For both flexible and rigid pavements, the PCR is calculated using layered elastic analysis in which the subgrade strength is characterized by modulus of elasticity, *E* (rather than CBR or *k*). Thus, the ACR/PCR method defines a single, unified set of four standard subgrade categories based on E, which applied to both types of pavements. In a further departure from the ACN system, the standard number of coverages for computing flexible ACR has been raised from 10000 to 36500. The pavement response to the main landing gear is still related to a mathematically derived single wheel load (DSWL), but the standard tire pressure has been increased to 1.5 MPa (218 psi). While ACN in all cases determined the DSWL from a single main landing gear group (for example, a four wheel group in the case of a dual-tandem gear), the ACR method for flexible pavements considers the contribution of all tires in the main landing gear (Rigid ACR continues to be based on a single main gear group).

Table 3 lists the elastic properties of the standard pavement layers used to compute rigid and flexible ACR. In addition to the listed properties, a large number of other parameters of the computation must be defined, including the method of assigning variable elastic properties to aggregate base layers, the functional relationship between computed strain and allowable coverages (the failure model), and the exact locations of layered elastic strain evaluation points. Due to the complexity of the computation, it must be performed by a standard computer program. The standard program adopted by ICAO for this purpose is *ICAO-ACR*, which is supported by the FAA and is available as a standalone program or as a dynamic-link library (DLL) for linking to other programs (for example, for PCR computation). The FAA's pavement design software *FAARFIELD* (beginning with *FAARFIELD* version 2.0) incorporates *ICAO-ACR* as part of its PCR computation function.

Table 3 - Standard pavement structures for ACR computation

	Rigid	Flexible	
MLG Type	All MLG Configurations	Aircraft with 1 or 2 Wheel MLG	Aircraft with more than 2 Wheels in MLG
Surface Layer	E_1=27 579 MPa, v_1=0.15, t_1 is the design variable	Hot-Mix Asphalt E_1=1379 MPa, v_1=0.35, t_1=76 mm	Hot-Mix Asphalt E_1=1379 MPa, v_1=0.35, t_1=127 mm
Base Layer	E_2=500 MPa, v_1=0.2, t_2=200 mm	Crushed Aggregate E_2=f(t), v_2=0.35, t_2 is the design variable	Crushed Aggregate E_2=f(t), v_2=0.35, t_2 is the design variable
Subgrade Layer	Subgrade A,B,C, and D – infinite depth	Subgrade A,B,C, and D – infinite depth	Subgrade A,B,C, and D – infinite depth

The ACR-PCR system is structured so a pavement with a particular PCR value can support an aircraft that has an ACR value equal to or less than the pavement’s PCR value. This is possible because ACR and PCR values are computed using the same technical basis.

Computation of the ACR requires detailed information on the operational characteristics of the aircraft, such as maximum aft center of gravity, maximum ramp weight, wheel spacing, and tire pressure. The ACR-PCR method adopts four standard levels of subgrade strength for rigid and flexible pavements. These standard support conditions are used to represent a range of subgrade conditions as shown in Table 4.

Table 4 - Standard subgrade support conditions for ACR calculation

Subgrade Code	Subgrade Strength Level	Subgrade Modulus of Elasticity, E
A	High Strength	200 MPa (29008 psi); Represents all values of E ≥ 150 MPa
B	Medium Strength	120 MPa (17405 psi); Represents all values of E in the range 100 ≤ E < 150 MPa
C	Low Strength	80 MPa (11603 psi); Represents all values of E in the range 60 ≤ E < 100 MPa
D	Ultra-Low Strength	50 MPa (7252 psi); Represents all values of E < 60 MPa

For rigid and flexible pavements, the aircraft landing gear support requirements are determined by the layered elastic method for each subgrade support category (this marks a significant analytical departure from previous methods).

Using the parameters defined for each type of pavement section, a mathematically derived single wheel load is calculated to define the landing gear/pavement interaction. The derived single wheel load implies equal stress to the pavement structure and eliminates the need to specify pavement thickness for comparative purposes. This is achieved by equating the thickness derived for a given aircraft landing gear to the thickness derived for a single wheel load at a standard tire pressure of 218 psi (1.5 MPa). The ACR is defined as two times the derived single wheel load (expressed in hundreds of kilograms).

Because aircraft can be operated at various weight and center of gravity (cg) combinations, ICAO specifies three standard operating conditions for determining ACR values: the maximum ACR which is determined at the combination of the weight and cg to create the maximum ACR value, the relative ACR at a weight with a cg used to calculate the maximum ACR value and the tire pressure at the maximum gross weight, and the specific condition ACR with the cg and tire pressure adjusted for a specific gross weight.

To standardize the ACR calculation for flexible pavement the derived single wheel load is calculated at a constant pressure of 218 psi (1.50 MPa) relative to a total thickness t computed for 36500 passes of the aircraft. To standardize the ACR calculation for rigid pavements, a standard stress is stipulated as σ = 399 psi (2.75 MPa). Note the working stress used for the design has no relationship to the standard stress used for pavement strength reporting.

A convenient tool exists to ease the computation of ACR, ICAO-ACR (provided by the FAA). FAARFIELD 2.0 (also provided by the FAA) can also be used to compute ACR, but its prime focus is on the analysis of pavements and the generation of PCR by technical evaluation.

4.1.4 Airplane Classification Number/Pavement Classification Number (ACN/PCN)

In the interest of unifying airfield weight bearing reporting, which relates closely to flotation, the ACN/PCN has been devised by an international pavement strength study group for the ICAO. ACN is a number which quantifies the relative effect in pavement stress of an aircraft. For rigid pavement, it is quantified for a standard working stress of about 400 psi (2.75 MPa) at four standard subgrade values, their English equivalents being approximately k = 554, 296, 148, and 74 lb/in^3 (150, 80, 40, and 20 MN/m^3). For flexible pavements, ACN is quantified for a standard level of 10000 coverages for four standard subgrade values of CBR = 15, 10, 6, and 3. For either type of pavement, their corresponding strengths are termed high, medium, low, and ultra-low. The pavement response to the main landing gear is related to a mathematically derived single wheel load (DSWL) with a standard tire pressure of approximately 180 psi (1.25 MPa). A high ACN indicates that a strong pavement is required. PCN is determined by the airfield authorities by their own procedures and is the maximum ACN permitted on their airfield. For PCN purposes, tire pressure limits may be specified by these authorities as: unlimited, having no limit on pressure, high, limited to 254 psi, medium, limited to 181 psi, and low limited to 72 psi (1.75, 1.25, or 0.5 MPa, respectively). The necessary condition for a given aircraft to be acceptable for operation on a given pavement on an unrestricted basis is then ACN less than or equal PCN. The term unrestricted operations does not mean unlimited operations. The term unrestricted operations indicates that the aircraft is permitted to operate without weight restrictions, subject to tire pressure limitations. ICAO officially adopted the ACN/PCN method in 1981. Currently most countries report PCNs for their major international airports and many domestic airports. ACN/PCN is currently the preferred method of reporting pavement ratings worldwide and will remain useful during the transition to ACR/PCR. Details of the procedure are published in ICAO Annex 14 (reference [48]) and in Part 3, Aerodrome Design Manual (reference [8]).

4.1.5 Comparison of ACR and ACN methods

There is no mathematical correlation between the previous ICAO pavement strength reporting ACN-PCN and the new ICAO ACR-PCR system. Those who are already familiar with the ACN/PCN system will note that the resulting ACR values are on the order of ten times greater than the corresponding ACN value. This change was intended to allow easy comparison between the two methods, but at the same time, avoid confusion during transition to the new system. The introduction of ACR/PCR is not expected to drive changes to aircraft or landing gear configuration but should provide refined analysis of various pavement surfaces. For illustration purposes only, a comparison of the two methods is shown in Table 5. It should be noted that the relevant PCR and PCN for comparison will also be different, so direct comparison of ACR and ACN values will not provide constructive information.

Table 5 - Comparison of ACN and ACR for several aircraft

Aircraft	Technique		Subgrade			
			A	B	C	D
BAe-146 (95000 pounds (43t) GW)	ACN	Flexible	20.8	22.2	25.4	29.1
		Rigid	22.8	24.6	26.2	27.6
	ACR	Flexible	179.4	205.6	229.3	268.4
		Rigid	242.6	260.0	272.1	284.2
Airbus A350-900 (601650 pounds (273t) GW)	ACN	Flexible	67.4	71.8	81.7	112.8
		Rigid	65.0	72.5	84.5	98.1
	ACR	Flexible	680.3	692.5	742.2	883.9
		Rigid	729.4	825.4	917.9	1031.5
Boeing 777-300ER (777000 pounds (352t) GW)	ACN	Flexible	63.8	71.3	89.4	120.4
		Rigid	66.1	85.8	109.9	132.0
	ACR	Flexible	574.9	628.2	786.7	1232.8
		Rigid	728.5	1003.0	1175.2	1356.6

4.2 Unsurfaced Methods

4.2.1 U.S. Air Force Unpaved Surface Method

Since unpaved surfaces are generally, but not always, of much lower strength than paved surfaces, aircraft use of unpaved surfaces is of a more limited and marginal nature compared to the normal long term usage of paved surfaces. Flotation in unpaved surfaces is very sensitive to tire contact pressure, and it is cautioned that the methods developed are inadequate to quantify behavior except in a general way. Since operation on unsurfaced fields is important to the military, the Air Force, based on work done by the Army Corps of Engineers, has published ASD-TR-68-34 (reference [29]). The term unsurfaced soil is used to differentiate from pavement. Also, the term unsurfaced soil excludes covering with mats or membranes, which are classed by the military as expedient surfacing described in 4.3. It should be noted that the presence of turf is not considered helpful in improving the soil strength.

ASD-TR-68-34 analyzes flotation for both the nose and main gear, based on a 3.0 inch rut depth and uses the maximum loading on each as a function of cg. In the case of nose gear load, the incremental load due to braking is added to the static load. In lieu of tire inflation pressure, the method uses tire contact pressure derived by dividing the SWL by tire contact area per the method specified. The remaining input parameter is wheel spacing in multiwheeled gears. Using these inputs, the CBR for one coverage is calculated; and results converted to other coverage levels using a graph provided. After coverages are converted to passes for the most critical nose and main gear loads, these are algebraically combined to determine aircraft flotation. The method lends itself to desk top calculation, although it is frequently computerized. No unsurfaced field procedure includes the effect of steering.

4.2.2 Tire Inflation Pressure Approach

Outside the United States, occasional operation into and out of unpaved airports is not uncommon even for large commercial transports. Although there is no general agreement between operators on all facets of unpaved field operation, including flotation, it has become acceptable to consider tire inflation pressure a single most important criterion for flotation. Perhaps Australia has more airports subject to this restriction than any other nation. Even at paved airports in Australia, an aircraft meeting LCN requirements may be prohibited from operating there on the basis of tire pressure. In any event, the analyst should be aware of this situation in Australia in particular, and third world nations in general, where operation other than at large municipal airports is contemplated.

4.2.3 Grass-Covered Airfields

Grass-covered airfields are considered to be similar to bare soil fields, although, apart from flotation, they may vary with respect to their nonuniform conditions such as surface roughness, braking coefficients, and rolling resistance. In general, to maximize performance, the grass should be cut short, but the turf and sod root structure should not be disturbed. Analysis is best performed by utilizing Cone Index, Airfield Index, or CBR.

4.2.4 Snow Runways

The strength of snow is highly variable and depends on the amount of compaction (density), age hardening (sintering), and temperature. A prepared, compacted snow runway can be considered analogous to an aggregate surface runway. Rather than CBR as a measure of the strength of the snow (CBR measurements are difficult to conduct in Polar environments and not appropriate for soft snow), varying cone penetrometers are employed. An empirical relationship [40] has been developed to relate the required ram hardness (units resulting from the use of the Rammsonde cone penetrometer) to the wheel load, contact pressure, and coverages. It is important to note that naturally occurring snow is unlikely to have sufficient strength to support wheeled aircraft; a C-130 requires a ram hardness of about 500, a DC-3 a ram hardness of about 250. Experimental work in Antarctica using specialized snow milling machinery, grading, and levelling have achieved ram hardness values over 300 and multiple additional compacting runs have achieved ram hardness levels of more than 600.

4.2.5 Ice Runways

The behavior of ice is similar to that of concrete – it is strong in compression but relatively weak in tension. In addition, it has very low fracture toughness. The properties of ice vary depending on the type of ice, the density, and temperature. In general, ice tensile strength [41] varies between 0.7 and 3.1 MPa while the compressive strength is between 5 and 25 MPa (725 and 3626 psi) for temperatures between -10 and -20 °C (14 and -4 °F). It is possible to analyze ice sheet runways as if they were rigid pavement runways, but with the appropriate properties for the relevant ice. The flexural strength used for the now defunct Pegasus glacial ice runway in Antarctica was 39.2 kPa (5.7 psi). Operating a C-17 at 263 tons (579816 pounds) mass requires an ice thickness of 2.25 m (7.4 feet) (safety factor 1). Considering a safety factor of three, a thickness of 6.8 m (22.3 feet) is recommended. The thickness of the Pegasus ice sheet was around 30 m (98 feet) while the Wilkins runway in Antarctica is estimated to have a thickness of around 700 m (2300 feet). The use of proof rollers (rolling the surface with a load and tire pressure similar to the aircraft) prior to utilization of the runway is recommended to ensure that the ice surface will withstand the aircraft loads. Glacial runway surfaces are often topped with 'white ice' pavement – a pavement made from compacted and frozen snow. This white ice helps protect the ice surface from solar radiation and melting and provides better friction characteristics for braking and maneuvering. The white ice layer, being compacted snow, is similar to a prepared snow runway and must be tested to ensure that there is sufficient strength to resist the contact pressure from the tires. Typically, a penetrometer such as the Russian snow penetrometer or a dynamic cone penetrometer is used. These penetrometers are similar but enhanced versions of the Rammsonde penetrometer. Tire pressure dominates the local behavior of the white ice pavement – hardness values for various aircraft and required snow hardness versus tire pressure are provided in U.S. Air Force document FC 3-20-06F [42].

An analysis for wheeled aircraft operation on sea or fresh water ice is best performed with expert information on the strength of ice. Sea and fresh water ice have a significantly larger flexural strength than glacial ice; as a result, a much thinner layer of ice can support an aircraft compared to glacial ice. However, the strength of ice remains highly variable and depends on a variety of factors, including the ice temperature and the temperature history (ice can become brittle following a significant drop in temperature). Three aspects need to be considered for operating an aircraft on a floating ice sheet: the strength of the ice, the creep deformation of the ice for stationary loads, and the dynamic behavior of the ice and supporting water during aircraft movement. Transport Canada provides relevant guidance for ice runway strength and operation in their Advisory Circular AC 301-002 [43].

4.3 Expedient Surfaces

Landing mat is used when strength or smoothness of airfield surfaces is otherwise not adequate. Membrane surfacing is used where soil strength is adequate but where subsequent wetting may otherwise lead to reduction in soil strength to less than that needed. Description of mat and membrane types, airfield design and construction requirements, placement techniques, anchorage of the surfacing, and maintenance procedures are discussed in detail in TM 5-330 (reference [30]), and TM 5-337 (reference [31]).

4.3.1 Landing Mats

Three general categories of landing mat have been established: one for heavy duty, one for medium duty, and one for light duty. The heavy-duty mat is capable of sustaining 1000 coverages of a 50000 pounds (222 kN) single-wheel load, with a tire inflation pressure of 250 psi (1.72 MPa), and tire contact area of approximately 200 square inches (0.129 m^2) when placed on a subgrade with an airfield index of 6 (CBR of 4). The medium-duty mat is capable of sustaining 1000 coverages of 25000 pounds (111 kN) single wheel load with a tire inflation pressure of 250 psi (1.72 MPa), and tire contact area of approximately 100 square inches (0.065 m^2), when placed on a subgrade with an airfield index of 6 (CBR of 4). Mats have been developed that meet all requirements for heavy and medium-duty usage, but mats that will meet all the requirements for light-duty usage are not available.

4.3.2 Membranes

Requirements for the development of three classes of membranes have been identified for aircraft traffic areas of various landing facilities. These are heavy, medium, and light duty membranes. The heavy duty membrane is the first of this family of membranes developed to date and is capable of withstanding wheel loads of all army aircraft and the Air Force C-130 aircraft with gross weights up to 155000 pounds (70310 kg) during a service life period of 2 weeks to 12 months. Medium and light duty membranes are currently under development in addition to an extra-light duty membrane for use in nontraffic areas and under landing mats.

Membranes are often placed under landing mat in high traffic areas, i.e., runways and taxiways. In this case, the membrane provides a waterproof covering for the soil. Membrane is also used to provide dust control in aircraft traffic areas where otherwise dust would be too great a problem and chemical dust palliatives are either less satisfactory or require greater time or effort to place.

4.4 Aggregate (Gravel) Airfields

Gravel and bare soil surfaces are analogous in relation to surface strength assessment for flotation and can be analyzed for flotation by ASD-TR-68-34. Gravel, however, consists of a layer of aggregate over the soil subgrade. As such, the thickness of the gravel layer in relation to the subgrade strength and the spacing of multiple-wheels can become a primary factor in flotation analysis. In general, aggregate runways are typically addressed through tire pressure limitations (as the surface shear strength is typically the dominant factor for this type of runway's strength). Transport Canada provides guidance [46] based on the Boeing company method of relating tire pressure to surface CBR [47].

5. OBSOLETE FLOTATION CRITERIA

In the course of a survey of flotation literature, or research of previous aircraft flotation analyses, the analyst is likely to encounter criteria no longer recommended for use by their originators, or which have not been in general use in favor of other, more widely accepted criteria. Table 6 lists documents which fall in this category. However, this does not necessarily mean that a method listed here may not be specifically required by a customer in the future.

Table 6 - Obsolete flotation criteria

The Unit Construction Index Chart for Aircraft Ground Flotation Evaluation, Technical Memorandum Report WCLS 53-13	Superseded by WES Misc. Paper 4-459	(1)
Construction Index, Miscellaneous Paper No. 4-100	Superseded by WES Misc. Paper 4-459	
Developing a set of CBR Design Curves, WES Instruction Report 4	Superseded by Instruction Report S-77-1	
Evaluation of Aircraft Landing Gear Ground Flotation Characteristics for Operation from Unsurfaced Soil Airfields, SEFL Report 167 (2)	Superseded by ASD-TR-68-34	
Aircraft Ground Flotation Procedures - Paved Airfields, SEG-TR-67-52	Superseded by ASD-TR-70-43	(3)
Evaluation of C-5A (CX-HLS) Aircraft Ground Flotation Characteristics for Operation from Flexible Pavements, SEFL 165A	Superseded by ASD-TR-70-43 for military, commercial, and civil still use	

NOTES:

(1) WES MP 4-459 was produced to provide a comprehensive methodology for aircraft flotation analysis. As such, it would supersede prior criteria as indicated. While the criteria remain valid for flotation analysis, they must be considered somewhat obsolete in that they have not been specifically applied to any aircraft procurement nor have been commonly applied in any manner.

(2) The unsurfaced landing strip criteria in SEFL 167 are the same as in WES MP 4-459 but because of the obsolescence of the MP (see Note (1) above), cannot be considered to be superseded by the MP. However, the SEFL 167 report was primarily used in connection with C-5A assault field operational capability and is not - because of older date - considered obsolete.

(3) While SEFL 165A retains its original validity, it also was primarily for C-5A performance. As indicated, it is superseded by ASD TR-70-43 for military purposes. It may still be used by some for commercial and civil purposes. Primary difference between SEFL 165A and the ASD TR-70-43 is in the adjustment (in SEFL) of deflection factors (to 20 radii offset) used in determining ESWL. For many-wheeled aircraft, the two could yield quite different ESWL values.

5.1.1 Portland Cement Association (PCA)

Many airport pavements have been designed using the method published by the Portland Cement Association. This association has developed basic data from which to design rigid (concrete) pavements for airports. In 1955, PCA published a manual: "Design of Concrete Airport Pavement." This was revised in 1973 and is a standard reference for concrete pavement design (reference [10]). The manual is based on Dr. H. M. Westergaard's method of theoretical analysis published by the American Society of Civil Engineers and includes the Influence Chart method developed by Dr. G. Pickett and G. K. Ray (reference [11]) and computer methods by Robert H. Packard.

Although some methods have assumed that the subgrade is an elastic solid, Westergaard assumed it to be a dense liquid. His assumption has general acceptance and is used by PCA. Influence charts for interior slab loading and edge loading have been made to determine either pavement deflection or stress, the latter being the one normally used for landing gear flotation evaluation. Use of this method involves making a tracing of the tire footprint pattern of the given landing gear to a scale based on the pavement parameter, radius of relative stiffness "l" and influence chart size. With these inputs the tracing is drawn to a scale matching that of the influence chart illustrated in Figure 8. By counting the blocks which are covered by the tire footprint on the tracing, pavement moment is determined. Larger influence charts are available from the Portland Cement Association under the designation Extension Chart No. 2.

Maximum moment is obtained by rotating the tracing to successive positions on the chart. Maximum stress is obtained by dividing the maximum moment by the pavement section modulus as shown at upper right of Figure 8. The technique is sufficiently accurate for most purposes; however, it is tedious to use. To overcome this objection, the PCA has developed a set of design curves applicable to certain standard landing gear arrangements. A computer program can also be obtained from them to calculate pavement stress for any gear arrangement and position for maximum moment (see reference [12]).

The PCA manual also specifies thickness of concrete overlay required to strengthen existing pavements. By virtue of the adoption of the PCA method by the Aircraft Industries Association (see 4.1.2) it is a widely used rigid pavement flotation criterion in the United States.

5.1.2 Pavement Design Using Layered Elastic Theory

Procedures have been developed by the Shell Oil Company, Asphalt Institute, Corps of Engineers, and the Navy in which the airfield pavement structural section is represented as a multilayer elastic solid and incorporates the concept of limiting tensile strain in the surfacing layer and vertical compressive strain in the subgrade. The Shell method is for a pavement structure consisting of asphalt concrete, untreated granular base, and subgrade of asphalt concrete directly on the subgrade (see reference [13]). The Asphalt Institute method is limited to asphalt concrete placed directly on a prepared subgrade (see reference [14]).

Both the Army and Navy have authorized optional designs (reference [15]) using layered elastic theory procedures for pavements composed entirely of asphaltic concrete. For Navy airfields, the procedure is documented in reference [16]; and reference [17] contains the Army procedure. The Army procedure is not limited to pavements composed entirely of asphalt concrete but can handle conventional flexible pavements as well as pavements having stabilized layers.

In addition to flexible pavement design, the Corps of Engineers also has developed a design procedure for rigid (jointed Portland cement concrete) pavements based on layered elastic theory. This procedure is contained in reference [18].

The Corps of Engineers procedure for both flexible and rigid pavement have been incorporated into design manuals (references [19] and [20]).