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AEROSPACE INFORMATION REPORT

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AIRCRAFT FLOTATION ANALYSIS

1. BACKGROUND AND PURPOSE: Aircraft flotation analysis is characterized by a variety of methods which lead to confusion. Sources of this variety are at least fourfold. To begin with, the foundation of all runways and taxiways is soil, which is not a homogeneous material. Not only does it vary widely from place to place, but it also varies with time 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 methods of approach 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 interested in operation on unpaved areas, such as mats, membranes, and unsurfaced soil.

Although the 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 method of reporting aircraft flotation has been devised which focuses on a meaningful value. This method, termed ACN/PCN has broad support in the western world; and has been adopted by the International Civil Aviation Organization (ICAO) as a single airfield weight bearing reporting method. It might well become the basis for a widely accepted and understood aircraft flotation methodology. Until such time, however, 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 report is to inform the aircraft flotation analyst of the various methods likely to be used and characterize them for evaluating the capability of aircraft to operate on airport runways and taxiways.

2. SCOPE: The substance of this report 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 the various methods used. To accomplish the minimum intent of this report, techniques could be limited to those needed for flotation analysis only. Because of the close relation between flotation analysis and runway design, methods for the latter are included. In fact, runway design criteria are used for flotation and evaluation in some cases, and are periodically the governing procedure in specific, if isolated, instances. From time to time, it may be necessary to deal with runways built to obsolete criteria. Therefore, a listing of most of these constitutes the third part. The fourth part of this report tabulates the recommended documents, categorizing them for commerical and civil versus military usage, by military service to be satisified, and by type of runway. The report is concluded with brief elaborations of some concepts for broadening the analyst's understanding of the subject.

3. FLOTATION ANALYSIS FEATURES AND DEFINITIONS: In order for the aircraft designer to ensure 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 4.0.

3.1 Flotation Definition: Flotation, as used for aircraft operating on land, refers to the capability of the airplane to operate on a surface in an effective manner. Aircraft flotation deals with runways and taxiways that may be surfaced, using pavement or other strengthening means, or unsurfaced. It has as its object suitable life of the surface and acceptable aircraft operation thereon.

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 4.0, 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.

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 floation technology were extended to accommodate the multiple-wheel loadings by establishing the concept of ESWL.

3.2.1 Definition of ESWL: ESWL is the load on a single-wheel which has a requirement for supporting pavement structure equivalent to that of a particular multiple-wheel (dual, dual-tandem, or more complex) configuration and load. Since the ESWL is a conceptual load on a single tire larger than the load on one tire of the multiple wheel configuration it represents, and since load relates directly to pressure and tire contact area (see 3.2), it is necessary to arbitrarily select some aspect of the pressure-contact area relation in order to specifically evaluate ESWL for design or floation. This can be done--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), makes use of the contact area of one wheel of a multiple-wheel gear to define ESWL for flexible pavements. For Load Classification Number (LCN) purposes discussed in Paragraphs 3.4.2 and 4.1.10, the British select the tire pressure of the multiple-wheels and let contact area increase to permit the determination of ESWL; and this has been done commonly by others. 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 established uniquely for selected critical depths only. This selection is based directly on depth (thickness) of pavement structure for flexible pavement and indirectly on radius of relative stiffness (ℓ) 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 or relative stiffness (ℓ), than for pavements on low strength subgrade (thicker pavement, larger ℓ).

3.2.3 Radius of Relative Stiffness: Radius of relative stiffness, which is a function of the parameters modulus of elasticity of the concrete, thickness, Poisson's ratio, and 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.

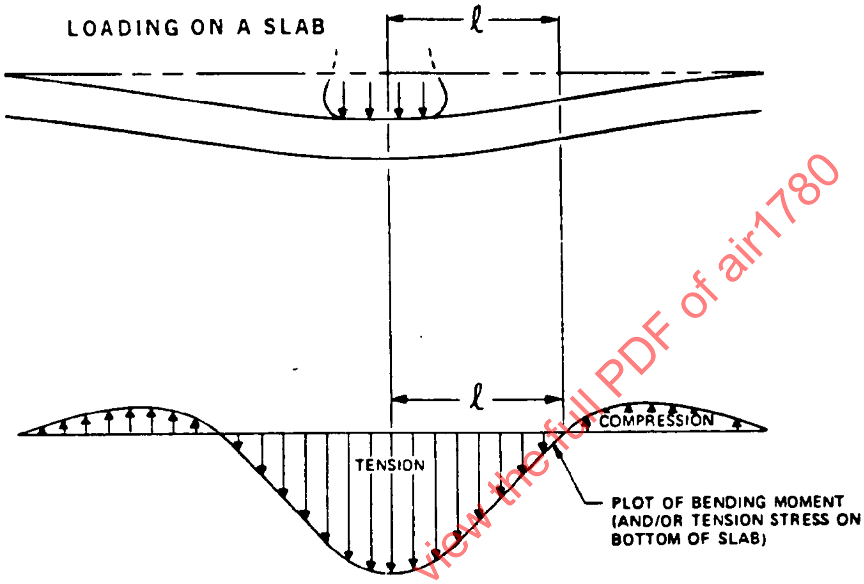


Figure 1. Physical Meaning of Westergaard's "Radius of Relative Stiffness," ℓ

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:

3.3.1 Paved Surfaces: 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. Also, taxiways are subjected to high frequency of load and are therefore correspondingly thicker than less critical areas. The FAA designates areas such as taxiways, ramps, and runway ends as critical; and areas such as the central or interior runway areas as non-critical. Depending on the design method used, the required thickness in non-critical areas is 80 to 90 percent of the depth required in critical locations. The military groups pavements into traffic areas. An example for a typical layout for heavy load Air Force pavements is shown in Figure 2.

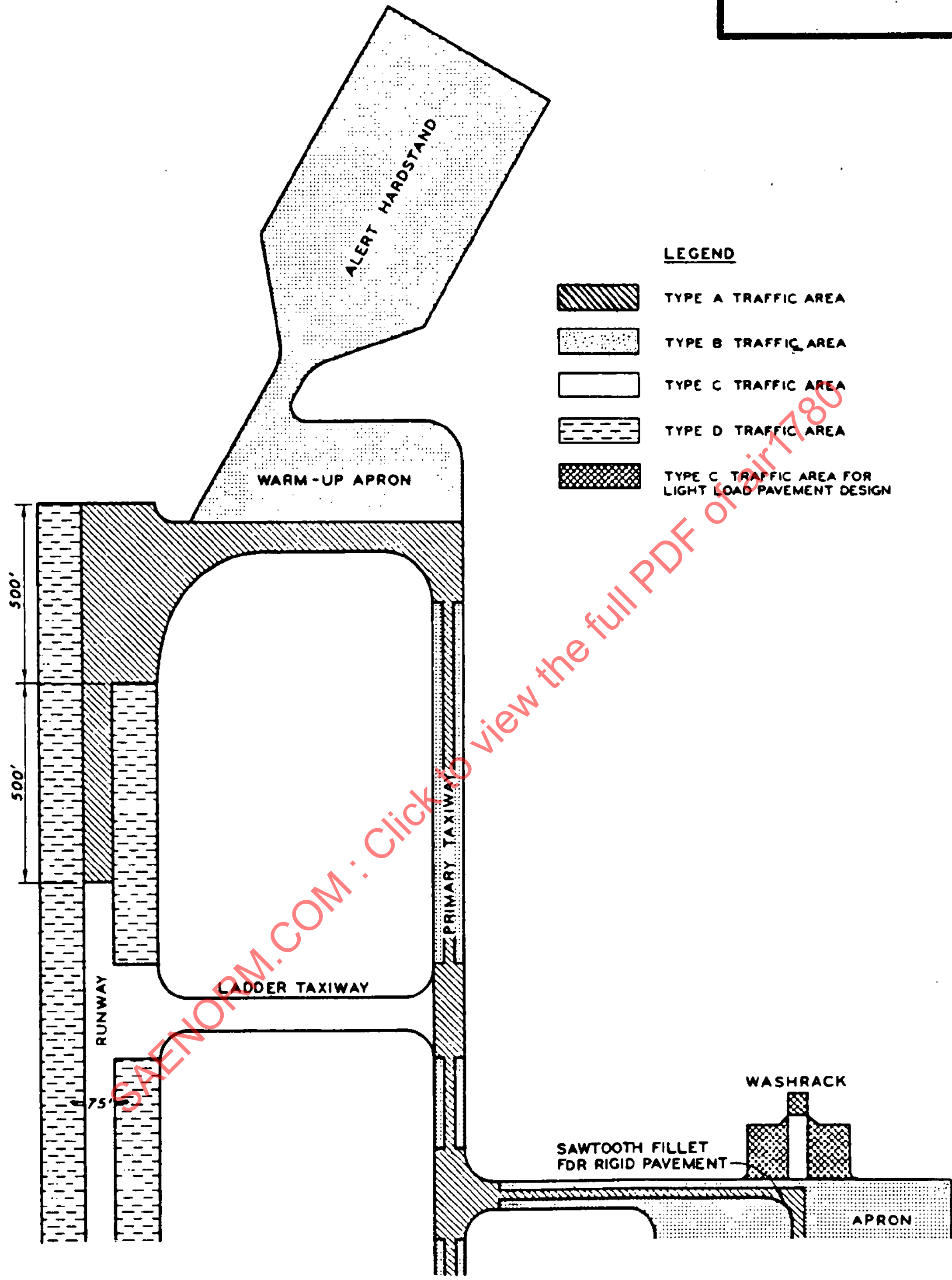


Figure 2. Typical Layout of Air Force Heavy - Load Pavements

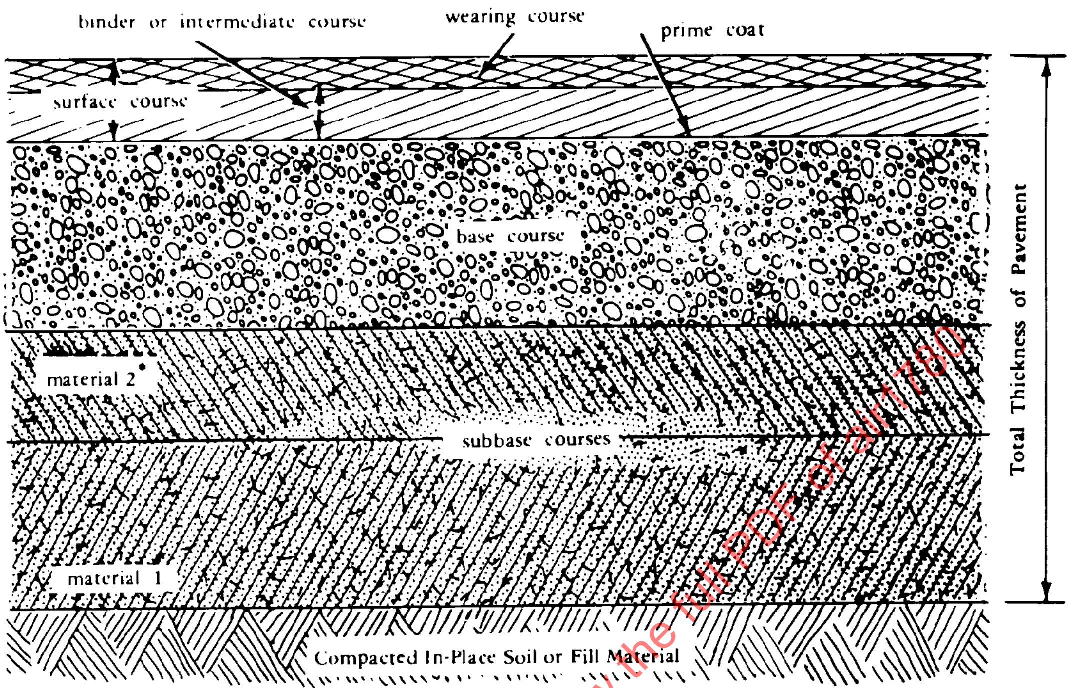
3.3.1.1 Rigid Pavements: Rigid pavements are all basically made of Portland Cement concrete. After initial construction they may be overlaid to increase their load bearing capability. The thickness of the pavement is the thickness of the concrete and does not include any strengthening layers between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

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. There is a trend to base the design on edge loading for heavy aircraft, but this is not universal. Corner loading has seldomly been considered in the United States.

Rigid pavement theory in the United States is all 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. Since certain problems in the application of the latter concept are unresolved, it is not used.

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 MN/m^2). This agrees with the nominal reported in Reference 3, which also states that the minimum safety factors for critical areas and non-critical areas are 1.75 and 1.5, respectively. In some instances the latter has been reported as low as 1.25 and as high as 2.0.

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 often of unprocessed material or material selected from a suitable source near the construction site. 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 150 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.



*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

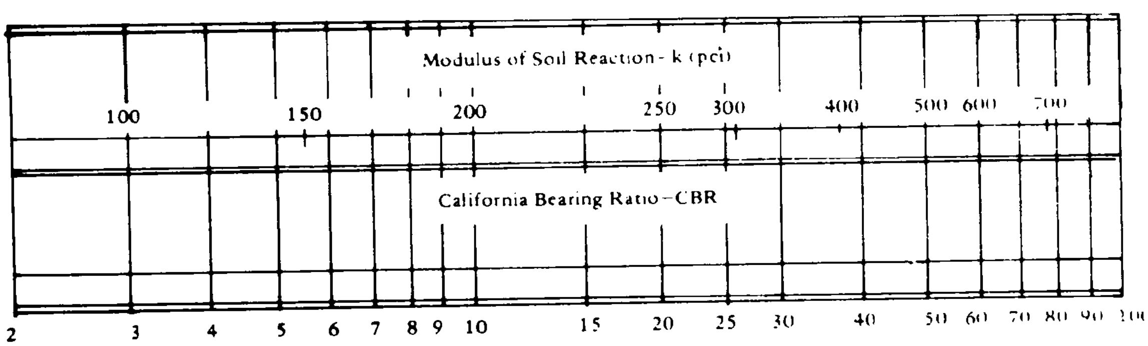
Figure 3. Typical Flexible Pavement and Terminology

3.3.1.3 <u>Other Pavements</u>: 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 structural 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 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 stabilizaton credit is given for increase in strength, whereas it is not for soil modification.

3.3.1.4 <u>Overlays</u>: Overlays of concrete or asphalt are used to strengthen rigid or flexible pavement. Overlays are most commonly flexible; but rigid overlays on rigid pavements are used, and rigid overlays of flexible pavements are somtimes employed.

3.3.2 <u>Subgrade Strength</u>: Subgrade strength is commonly defined by either the Modulus of Subgrade or Soil Reaction or California Bearing Ratio (CBR). The modulus of subgrade reaction, k, is defined as the applied load in lb/in^2 divided by the soil deflection in inches. Thus, k has the dimensions of lb/in^3, values usefully considered varying from 50 to 500 (13.6 to 135.7 MN/m^3). This modulus is the strength parameter typically associated with rigid pavements. 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 usefully 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.



Note: Conversion of the test results will not be used for design.

Figure 4. Approximate Interrelationship of Bearing Values

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 the 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.

3.4 Fatigue in Airfield Surfaces: Parameters, based on the use of an airfield, have been developed to address the surface fatigue.

3.4.1 Fatigue Factors U.S. Origin: There are several terms related to aircraft traffic on a pavement that have been used in airfield design. Among these are cycles of operation, aircraft passes, annual departures, takeoffs and landings, and so on. Those terms currently in use by the U.S. Military and Great Britain are aircraft passes whereas the FAA uses annual departures.

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 described in 4.1.7. In effect, they consider a takeoff and a landing two passes per their unsurfaced method related in 4.2. 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 5). 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.

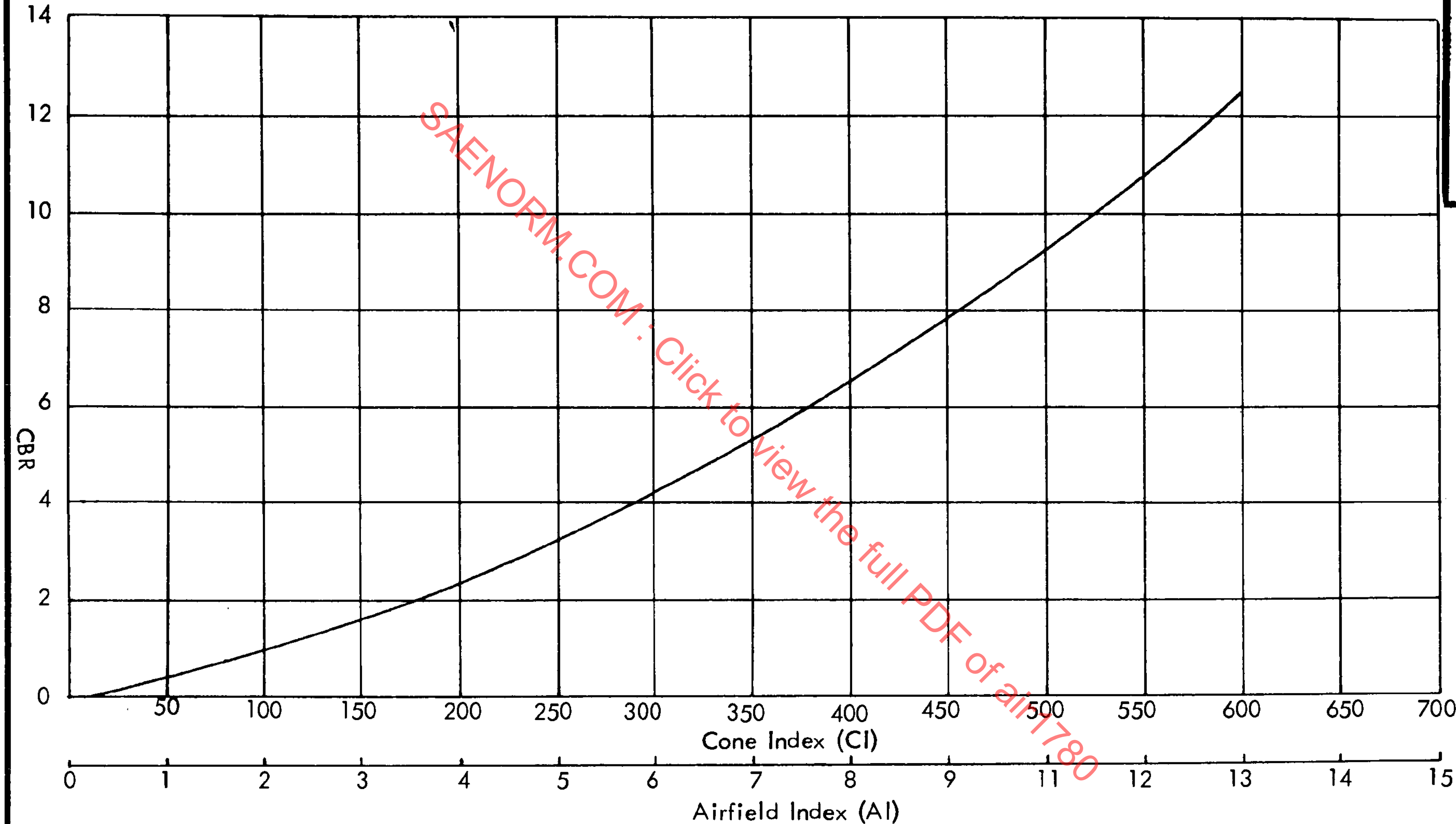


Figure 5. Correlation of CBR, CI, and AI - Fine-Grained Soils

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.

3.4.2 Fatigue Factors - Outside the U.S.: The Load Classification Number method (Reference 6) devised in the United Kingdom 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.

TABLE I
LCN FOR LIMITED PAVEMENT USE

Ratio of Aircraft LCN / Pavement LCN	Movements	Remarks
Up to 1.1	Unlimited	
From 1.10 to 1.25	3,000	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	

3.4.3 United Kingdom Traffic Categories: In the United Kingdom two categories of traffic are identified, channelized for taxiways and non-channelized for runways. The pass to coverage ratios (P/C) for various landing gear types for these categories are found in Table 2 (see Reference 7).

TABLE 2
CHANNELIZED AND NON-CHANNELIZED P/C IN THE UNITED KINGDOM

Gear Configuration	Pass to Coverage Ratio	
	Channelized	Non-Channelized
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

In their usage, a pass is 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:

4.1.1 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 8). 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 9) 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.

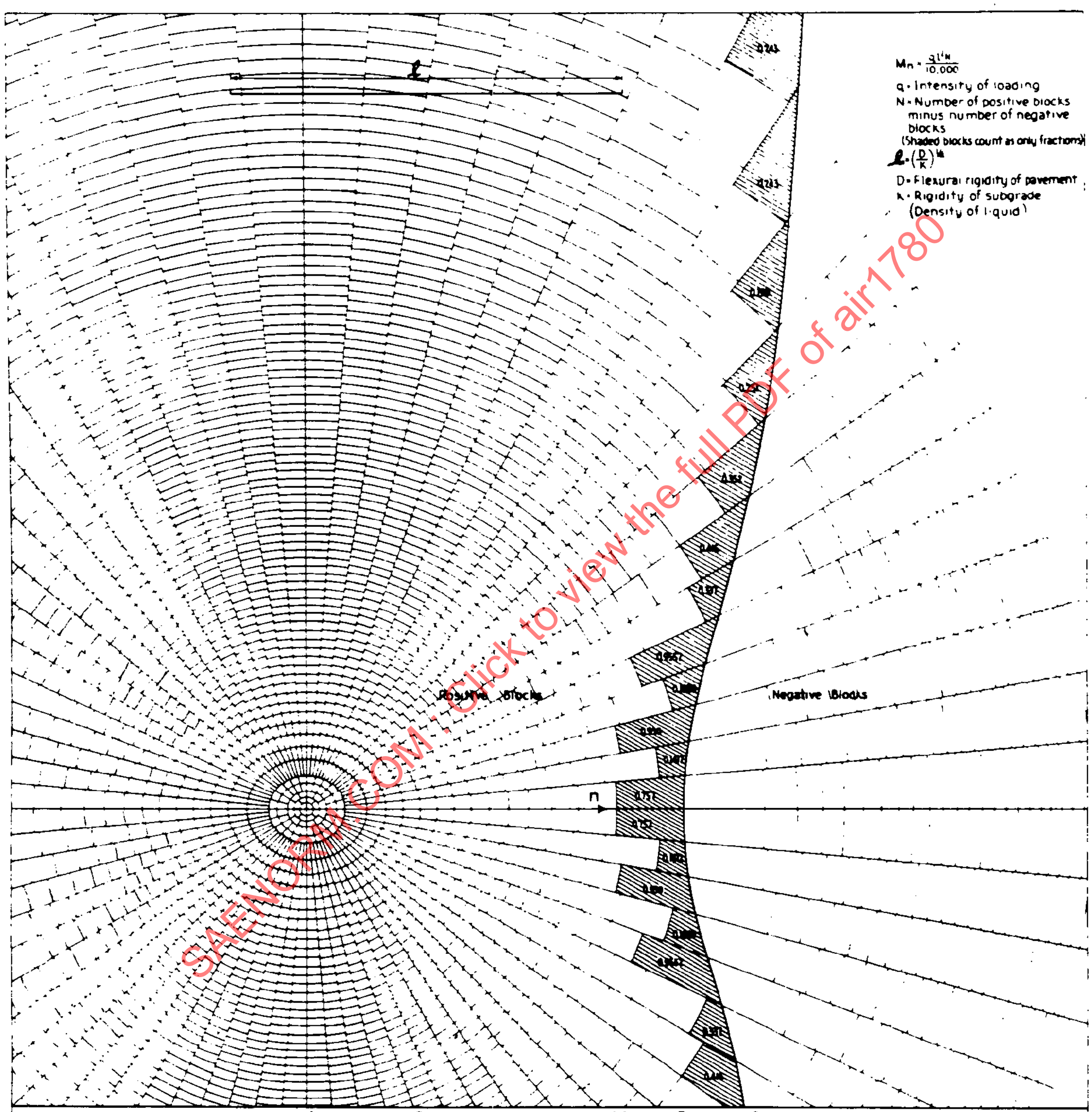
Influence charts for interior slab loading and edge loading have been made to determine either pavement deflection or stress, the latter being the one normally used for landing gear flotation evaluation. Use of this method involves making a tracing of the tire footprint pattern of the given landing gear 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 6. 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 Associaton 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 6. 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. This program by Robert G. Packard is entitled "Computer Program for Concrete Airport Pavement Design (Program PDILB)," Reference 10.

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 (Section 4.1.4 below) it is a widely used rigid pavement flotation criterion in the United States.

4.1.2 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 multi-layer 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 11). The Asphalt Institute method is limited to asphalt concrete placed directly on a prepared subgrade (see Reference 12).

Both the Army and Navy have authorized optional designs (Reference 13) using layered elastic theory procedures for pavements composed entirely of asphaltic concrete. For Navy airfields, the procedure is documented in Reference 14; and Reference 15 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.



INFLUENCE CHART FOR THE MOMENT M_n IN A CONCRETE PAVEMENT DUE TO A LOAD IN THE INTERIOR OF THE SLAB
(Subgrade assumed to be a dense liquid. Poisson's ratio for pavement assumed to be 0.15)

Figure 6. Influence Chart for Rigid Pavement Analysis

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 16.

Work is currently under way to incorporate the Corps of Engineers procedure for both flexible and rigid pavement into the tri-service pavement design manuals.

4.1.3 Port Authority of New York and New Jersey (PANYNJ): The Port Authority of New York and New Jersey has developed a pavement design concept of its own. The method was devised for reasons of economy realized by using locally available materials. The pavement is basically made of a mixture of lime, cement, and flyash (L-C-F) with sand, although where high strength base material is required, 30% by weight of crushed stone can be added. One of the features emphasized in the method is consideration of dynamic response of the pavement and its relative roughness to dynamic loads imposed by the aircraft. Other features are: (1) equivalent single wheel load analysis as a function of elliptical integrals, and (2) theoretical expressions for soil stress and deflection. Although it has been applied in the metropolitan area of New York City only, it needs to be considered for aircraft operating at airports under control of the Port Authority.

4.1.4 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 a National Aerospace Standard NAS 3601, entitled "Recommended Standard Data Format of Transport Airplane Characteristics for Airport Planning," Reference 17.

This standard includes flotation and specifies that rigid pavement flotation be prepared in general accordance with the PCA, but modified to format as described in the NAS. For this, the standard calls out "Computer Program for Concrete Airport Pavement Design," (PDILB), Reference 10.

Concerning flexible pavement flotation the standard calls for flotation to be determined based on the procedures set forth in SEFL Report 165-A, which was a C-5 study method not endorsed by the Air Force for use other than the C-5. Therefore, it is not included as a separate method in this report. Suffice it to point out that the concept used in SEFL 165-A is that a curve can be constructed which represents the required airfield strength in terms of CBR versus depth below the surface. If the curve for that airplane in question requires less strength at various depths below the pavement than the strength available at those depths, the aircraft flotation is acceptable. The method also identifies light, medium, and heavy load zone-of-the-interior airfields in terms of CBR verus depth. The AIA is in the process of superseding this callout with Instruction Report S-77-1, Reference 18.

For either rigid or flexible pavement flotation analysis, the standard requires flotation also be expressed as LCN calculated per the LCN method defined in Reference 6.

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.

4.1.5 Federal Aviation Administration (FAA) Old Methods: Pavements at most civil airports in the United States were designed and constructed in accordance with FAA Advisory Circular AC 150/5320-6 or -6A, "Airport Paving" (Reference 19). Both flexible and rigid pavements are covered by these circulars. Evaluation for aircraft usage is a reverse design process.

Pavement design charts for flexible pavements are provided for aircraft with single, dual, and dual tandem main landing gears. Each chart indicates the total pavement thickness required for critical areas as a function of subgrade class and aircraft gross weight. Chart construction is based on typical increase of tire pressure and wheel spacing for multiple wheel gears as a function of aircraft weight. ESWLs are determined by a graphical method.

Rigid pavements designed in accordance with these advisory circulars are based on the Westergaard interior loading analysis. A design chart shows the pavement (concrete slab) thickness required as a function of aircraft gross weight for single, dual and dual tandem gears. The subbase thickness required is a function of the concrete thickness and subgrade class. Pavement thickness required is based on arbitrarily selected increases in tire pressure and wheel spacing as a function of the aircraft weight. Working stress was established at 400 psi (28 kg/cm^2) and computed by the Pickett and Ray Influence Charts. The subgrade or subbase is assumed to provide a modulus of k = 300 lb/in^3 (21 kg/cm^3).

4.1.6 FAA New Methods: FAA Advisory Circular AC 150/5320-6C, dated 12-7-78, "Airport Pavement Design and Evaluation" (Reference 20) provides requirements based on revised methodologies for both rigid and flexible pavements. Design charts show pavement thickness required for single, dual, and dual tandem main landing gears for aircraft up to 400,000 lb (181,440 kg) gross weight. These charts assume that tire pressure and wheel spacing increase with gross weight. Individual charts are provided for each wide body aircraft using the actual landing gear characteristics. Pavement design life is based on a 20-year life for various number of annual departures for combined traffic related to the critical aircraft.

Pavements for the critical airplane required by -6C are generally thicker than required by previous FAA methods. An aircraft operator could be penalized unfairly if an existing pavement were evaluated using a method different from that employed in the original design. To avoid this situation, FAA's policy for evaluation states that is should be based on the method used for original design.

Rigid pavement design is based on the Westergaard analysis of an edge loaded slab resting on a dense liquid foundation. The edge loading stress is reduced 25 percent to account for load transfer across joints which are keyed or dowelled. Computer analyses were performed to determine the maximum stress for the critical orientation of the various gear arrangements.

The new -6C methodology for flexible pavement design is commonly referred to as the CBR method. Pavement thickness is a function of the subgrade's CBR, ESWL and annual departures. The ESWL for multiple wheel gears is based on Boussinesq's elastic theory with the ESWL contact area equal to contact area of one tire.

4.1.7 U.S. Air Force Paved Surface Method: For the immediate future, an applicable Air Force document for paved field flotation is ASD-TR-70-43, "Aircraft Ground Flotation Procedures - Paved Airfields," Reference 21. Flexible pavement analysis is an adaption of the CBR method, whereas the rigid pavement analysis is an adaptation of the influence chart approach. The CBR method, as used in preparing ASD-TR-70-43, was as described in Instruction Report 4 (Reference 22). This has since been superseded by Instruction Report S-77-1 (Reference 18), however, ASD-TR-70-43 is still approved by the Air Force.

For rigid pavement, the Air Force plans to replace the existing interior load basis with the edge load approach. Because of Air Force interest in operating on airfields in NATO and elsewhere outside the United States, their procurement documents more and more frequently are including analysis per the LCG method.

4.1.8 Tri Service (Army-Navy/Marine-Air Force) Pavement Design Criteria: A tri-service design manual (Reference 13) presents basic criteria for the design of flexible airfield pavements. The basic thickness design procedure used for all services is the Corps of Engineers CBR design procedure.

The Air Force design criteria for rigid pavements are contained in AFM 88-6 (TM 5-824-3), defined in Reference 23, and for the Army in TM 5-823-3 (Reference 24), and are based upon the Westergaard edge loading as modified by the Corps of Engineers to take into account full-scale accelerated traffic testing, small scale model testing, and experience. The Navy method for rigid pavement design is quite similar to that of the Army/Air Force except that the Navy method considers interior pavement loading to be critical while the Army/Air Force considers edge loading critical. Because of adjustments in resultant stress magnitudes, however, the Navy design method produces very nearly the same pavement thickness as the Army/Air Force method. The Navy's method is described in detail in manual DM-21 (Reference 25).

A tri-service design manual for rigid airfield pavements (similar to that published for flexible pavements) is being prepared by the Army Corps of Engineers. All three services will use the Westergaard edge loading for the basis of rigid pavement design.

4.1.9 Canadian Method: The Canadian method for the design of flexible pavements (Reference 6) was developed from tests and studies by the Department of Transportation begun in the early 1940s. This method is also known as the McLeod Method for Dr. N. McLeod, who developed a simple equation to relate the bearing strength at the top of the base course to the top of the subgrade. The equation is $t = K \log P/S$. Briefly stated, t = thickness of pavement structure; K = a constant depending on size of a loading test plate; and P and S are the loads carried at the top of the base course and at the top of the subgrade, respectively. These loads are those on a given plate size at a given deflection and a given number of load repetitions. Values of P and S are also used by the Canadians for calculating rigid pavement strength based on Westergaard's equations, however, they alternately use the influence chart approach.

4.1.10 Load Classification Methods: There are two unique systems, developed in Great Britain since World War II, for aircraft evaluation and pavement design. The first and older of these is called LCN method. The second and newer of these is called LCG method. Confusion has arisen because both methods utilize a load classification number and because a given ESWL generally yields different values of LCN, depending on which method is used. To resolve the confusion, Table 3, which follows the separate descriptions of each method, highlights the differences and applicability of each approach. Details of these methods can be identified from examination of Reference 6.

4.1.10.1 Load Classification Number Method: This method of aircraft evaluation and pavement design was formulated in the United Kingdom immediately after World War II. In 1956 it was adopted by ICAO and is probably used for flotation by more countries than any other method.

The method consists of graphically determining equivalent single wheel load (ESWL) using data from the landing gear tire footprint geometry and pavement parameters. Graphs are provided for standard footprint patterns to make this determination. By entering tire pressure and ESWL on a graph of tire pressure versus ESWL, the aircraft LCN is determined. Lines of constant contact area (EWSL/tire pressure) are also shown on the graph. At contact areas more than 200 in.^{2} (.129 m^2), the LCNs for rigid and flexible pavements are the same. Below 200 in.^{2} (.129 m^2), separate LCN lines are provided for rigid and flexible pavements. The tire pressure/contact area/ESWL graph is derived assuming that ESWL is proportional to the 0.44 power of contact area. Pavement LCNs are determined by a series of plate loading tests, or constructed to the desired LCN value in accordance with standard design curves.

TABLE 3. COMPARISON OF LCN AND LCG METHODS

LCN Method	LCG Method
Distinguishes between rigid and flexible pavements.	Essentially assumes a rigid pavement.
ESWL is a function of pavement structure: and	ESWL is based on a pavement structure having ℓ = 40 in. and k = 400 pci.
Requires that radius of relative stiffness (rigid) or pavement thickness (flexible) be known	Pavement data are not required.
Airfields rated by Load Classification Number (LCN).	Airfields rated by Load Classification Group (LCG) for ranges of airfield LCNs.

LCN Basic Equation

$$\frac{W_1}{W_2} = \left(\frac{A_1}{A_2}\right)^{0.44}$$

(Symbols defined below.)

LCG Basic Equation

$$\frac{W_1}{W_2} = \left(\frac{A_1}{A_2}\right)^{0.27}$$

(Symbols defined below.)

For acceptable usage of the aircraft on the pavement in question:

LCN method: $LCN_{aircraft}$ $LCN_{pavement}$

LCG method: $LCG_{lower\ limit}$ $LCN_{aircraft}$ $LCG_{upper\ limit}$

Both the LCN and LCG methods use the basic equations above with symbols defined as follows:

W_1 = basic SWL = 1000 LCN

W_2 = ESWL

A_1 = area of basic tire = W_1/P_1

A_2 = area of ESWL = W_2/P_2

P_1 = basic tire pressure = 70 + 0.5 LCN

P_2 = aircraft tire pressure

NOTE: The numerical values in the equation for P_1 predicated on ESWL expressed in pounds and P_2 expressed in psi.

The approach taken is that aircraft flotation is acceptable for unlimited operation at a given airport if the aircraft LCN is less than or equal to the pavement LCN. Limited operation has been addressed in 3.4.2, Table 1. The published LCN value of a given runway is ideally derived from analysis of plate bearing tests, but may have been established by the LCN rating of the largest airplane known to have been successfuly operated thereon. Accurate LCN analyses of runways have been made in Great Britain, Canada, Australia, New Zealand, and other British and ICAO influenced countries. Aircraft LCNs calculated by one method must not be referenced to airfield LCNs based on the other. Note also as pointed out in Table 3, the aircraft LCN being of function of ESWL for multi-wheel gears requires that the rigid pavement radius of relative stiffness or flexible pavement thickness be known to define aircraft LCN by the LCN method. Prior knowledge of the pavement structure is not required to determine LCN by the LCG method.

4.1.10.2 Load Classification Group Method: The experience gained in the design, evaluation and performance of pavements has led to modification of the LCN method. As far as the British are concerned the LCN method has been replaced by the LCG method, and the Aeronautical Systems Division of the Air Force adopted LCG as one of the acceptable methods of evaluating aircraft flotation. The extent to which it is adopted by other countries, who have used the LCN method for many years, remains to be seen. The LCG method also uses graphical means to determine ESWL although the graphs are different from one method to the other. The LCG graphs require tire footprint geometry, but require no pavement parameter input since it analyzes flotation on the assumption that the pavement is equivalent to a rigid pavement having a radius of relative stiffness of 40 inches. LCG has its own tire pressure/contact area/ESWL graph, assuming ESWL is proportional to the 0.27 power of contact area. The aircraft LCN is acceptable for unlimited operation, providing its LCN is less than the upper limit of the given pavement LCG. Aircraft LCNs derived by the LCG method are typically less than those computed using the LCN method.

It is expected that most U.S. Airports are conservatively rated in terms of LCN; however, a very comprehensive listing of reported airfield LCNs has been compiled by the Defense Mapping Agency. The listing (Reference 26) entitled "Automated Air Facility Information File" (AAFIF), can be provided to the user on magnetic tape.

Comparision of key features of the LCN and LCG methods is found in Table 3.

4.1.11 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 about 400 psi (2.75 MN/m^2 = 2.75 M Pa) 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 10,000 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 ACN procedure automatically adjusts tire pressure to approximately 180 psi (1.25 MN/m^2 = 1.25 M Pa). 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: high having no limit on pressure, medium limited to 218 psi, low limited to 145 psi, or very low limited to 73 psi (1.5, 1.0, or 0.5 M Pa, respectively). The necessary condition for a given aircraft to be acceptable for operation on a given pavement is then ACN $\leq$ PCN. While some time delay in applying ACN/PCN may occur, ICAO is expected to officially recognize the ACN/PCN method in November 1981 as Amendment 35 to Annex 14. Details of the procedure will be published via Part 3, Aerodrome Design Manual, (Reference 6).

4.2 Unsurfaced Methods:

4.2.1 U.S. Air Force Unpaved Surface Method: Since unpaved surfaces are obviously 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, "Evaluation of Aircraft Landing Gear Ground Flotation Characteristics for Operation from Unsurfaced Soil Airfields" (Reference 27). 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 Paragraph 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, using the maximum loading on each as a function of c.g. 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 multi-wheeled 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.

4.3 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.

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 50,000 lb (222 kN) single-wheel load, with a tire inflation pressure of 250 psi (1.72 MN/m^2), and tire contact area of approximately 200 in^2 (.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 25,000 lb (111 kN) single wheel load with a tire inflation pressure of 250 psi (1.72 MN/m^2), and tire contact area of approximately 100 in^2 (.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 155,000 lb (70,310 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 non-traffic 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 pallitatives are either less satisfactory or require greater time or effort to place.

4.3.3 Details: Description of mat and membranes types, airfield design and construction requirements, placement techniques, anchorage of the surfacing, and maintenance procedures are discussed in detail in TM 5-330 (Reference 28), and TM 5-337 (Reference 29).

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 4 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 4. 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 they 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 obsolescense 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.