Framework for Evaluation and Performance of Airport Pavements

M. W. Witczak, University of Maryland, College Park

Some general, but fundamental, concepts relative to airport pavement evaluation and performance are discussed. Current pavement design methodologies can be grouped into structurally (load) or functionally (safety and smoothness) oriented designs, depending on the selection of the failure criteria. Most present airport pavement design methods are structurally oriented, but it has been suggested that they should be functionally oriented and that different sets of functional criteria should be developed and applied for each pavement area (apron, taxiway, or runway). Pavement performance studies are commonly grouped into two major categories: structural evaluation and condition surveys. Each has a different set of desirable objects. The concept of a management type of approach to airport pavements is advocated in a systems framework proposed by the U.S. Army Corps of Engineers for the Federal Aviation Administration, but for this type of system or management framework to be effective, continuous feedback and verification studies of several key elements are mandatory. The key elements requiring verification are those relative to (a) the as-built pavement structure, (b) the design input variables, and (c) the performance output model. The two most important areas requiring accurate data collection relate to the in situ (equilibrium) response (i.e., the strength or modulus) of the subgrade soil and the actual aircraft traffic-mix information that is recommended to be used in a mixed traffic analysis. This information is vital if one is to be able to make reliable and meaningful decisions relative to the pavement management scheme. The feedback-verification part of the system is mandatory because it will provide (a) information about the exact in situ (operational) state of the pavement components, thus bridging the gap between what the designer has assumed relative to what actually exists; (b) a common procedure leading to the earliest recognition of impending major pavement distress; (c) a common basis for accurate decisions and efficient plans for corrective measures when necessary; (d) the required input for developing a major rehabilitation scheme; (e) a reliable methodology for assessing the remaining life of a pavement; and (f) an adequate and rational procedure for evaluating the load-carrying capacity of a pavement.

The general object of this report is to provide a framework for the evaluation and performance of airport pavements. To begin, several key words and concepts used in pavement technology will be defined to provide a mutual basis for discussion and understanding.

The pavement design procedures used today can be broadly grouped into two major categories: structural and functional. The main distinction between these categories is the way in which pavement failure is defined. The structural designs pertain to a study of either a portion (layer or layers) or of the entire pavement. Until recently, such designs have been the primary basis for use in both rigid and flexible pavement systems. The design philosophy centers on structural considerations such as limiting stresses, strains, or deflections in one or more critical pavement layers. In addition, these design systems are intimately tied together by (a) the type of theory used, (b) the specific method of material(s) characterizations, and (c) the distress or failure criteria used.

Using the current state of the art as a standard, many of the earlier pavement design procedures are empirical in that the prediction of the relevant distress parameter (e.g., stress) is related to a somewhat arbitrary or empirical state of failure. These approaches have now been upgraded, and several recent design procedures have been introduced that recognize that more than one structural distress mechanism may lead to pavement failure.

Although a universally accepted design method is not currently available, several organizations have implemented improved design systems. These include the Shell Oil Company (1), the Kentucky Highway Department (2, 3), and the U.S. Army Corps of Engineers (4), all of whom have developed design methods for flexible highways, and the Asphalt Institute (5) and Shell Oil Company (6), who have developed design procedures for flexible airport pavements. In addition, a National Cooperative Highway Research Project has recently been completed that develops a completely rational design method for flexible highway pavements (7). Such developments have improved the state of the art for structural design of flexible pavement systems to a level of rationality approaching that of the structural design methodologies for rigid pavements that have existed for some time.

The recent advances in design methodology (i.e., theory, material characterization, and failure criteria) are frequently described in the literature as rational, improved, fundamental, or mechanistic. The ultimate object is a true mechanistic solution; i.e., the development of a precise model to explain in a physical manner how any particular pavement defect or distress is produced. One final, but important, connotation of structural designs is the implicit assumption of load-associated distress manifestations. Regardless of the degree of sophistication of the method, structural design is based on structural distress and hence on structural failure.

Functional, as defined by Webster, means "designed or adopted primarily to perform some operation or duty." When applied to pavements, the term implies that pavement engineers assess the function of the pavement itself in ascertaining the failure criteria to be adopted. As a broad generalization, the function of an airport pavement is to safely and smoothly transfer aircraft between the terminal complex and the air by the most economical means. Thus, implicit with functional considerations are functional failure criteria relating to safety (e.g., skidding), smoothness (e.g., pavement roughness or unevenness), and economy.

At present, there are a wide variety of procedures used to quantify roughness as a measure of functional distress. One such approach is the use of a subjective qualitative rating by the user of the smoothness (roughness) of the pavement. In highway pavement analysis, such a rating is termed the serviceability and represents the ability of the pavement to serve its intended function at a specific time. Some examples are the present serviceability index or rating and the present performance rating, which has recently been changed to the road comfort index by the Roads and Transportation Association of Canada. Another common way of determining roughness levels is by physical measurements of the longitudinal roughness or profile of the pavement system by using such devices as profilometers and roadmeters. These devices measure either cumulative displacements per unit of length of pavement or some parameter referring to the statistical variance-of-elevation differences of two closely spaced points. One such parameter is the slope variance, which has been found through correlation studies to be the major factor affecting the serviceability value of a pavement.

The other techniques used to measure the functional level of pavements are considered to be more rational or mechanistic in their development and applicability. One such procedure is the power spectral density analysis, which is discussed by Yang in a paper in this Special Report. Another promising technique is the development of a mathematical model to predict aircraft response to a specific longitudinal airfield profile. This procedure is discussed by Gerardi in a paper in this Special Report. In essence, the output of this model is the vertical acceleration levels at various points within a moving aircraft generated by the interaction between the vehicle and the pavement roughness. The use of acceleration as a functional criterion is promising because such a variable can be viewed relative to subjective criteria such as thresholds of passenger discomfort or readability of instrumentation in the cockpit, or it can provide a meaningful parameter for a fatigue analysis of the aircraft frame itself.

Another important difference between structural and functional considerations relates to the fact that while structural conditions imply load-induced distress manifestations only, functional conditions encompass both load- and non-load-induced roughness (e.g., frost effects, differential settlements, high-volume-change soils, and material-variability effects). When structural designs are used, it is an a priori assumption that the non-load-associated distress mechanisms have been or will be accounted for in the design phase.

A functional distress or failure philosophy should be the ultimate goal for design of airport pavement systems. However, unlike highway pavements, an airport should logically possess different sets of functional criteria for each specific pavement area (e.g., runway, taxiway, and apron). In particular, a runway is a unique pavement area and differs from other pavement areas (highway and airport). On a highway pavement or an airport taxiway, the driver or pilot has a viable alternative or option to a rough pavement system, i.e., a reduction in speed. However, this option is not available for runway operations because a threshold velocity must be obtained for both takeoff and landing. It is also logical to surmise that the need for skid-resistant surfaces (another functional parameter) is greater on a runway facility than on other airport pavement areas.

Thus, there should be a major change in the design philosophy for runways to viewing functional requirements as more important than other types of criteria. The use of structural design methodologies have for years led engineers to the mistaken belief that the taxiway facility is the critical area of the airport pavement. This is undoubtedly true of structural distress considerations due to the critical combination of static loads and slow aircraft speeds, but the same failure criteria should not be used for runways.

It should be apparent that from a structural viewpoint, the ability to accurately and mechanistically evaluate various individual distress modes is an extremely important factor. However, the present evaluation lacks the true ability to transform the individual distress parameters into a functionally oriented design system. Additionally, such procedures do not directly consider roughness associated with nonload factors such as initial construction capabilities, frost effects, variable compaction, and high-volume-change soils. Thus, the ideal design procedure must eventually be based on functional failure considerations. However, the major distress modes must be evaluated mechanistically, and performance should be monitored directly from the specific material characteristics used in the pavement system. Continued research will be necessary to develop a procedure that combines both distress- and performance-oriented parameters into an integrated package based on functional criteria.

STRUCTURAL AND PERFORMANCE EVALUATION

Historically, pavement engineers have used various techniques to evaluate in situ pavements during the operational phase. Generally, these methods can be grouped into two basic types of procedures, each having important, but different, objects. These are (a) structural evaluation and (b) performance or condition surveys. Evaluation, in the strict definition of the term, implies a careful appraisal or ascertaining of a specific value or values. Performance, on the other hand, implies fulfilling or carrying out.

Thus, the major object of a structural evaluation of an airport pavement is to obtain specific quantitative measures of relevant in situ structural properties of the system (either the entire pavement or individual layers). The variables to be measured are directly dependent on the design model being used. Typical variables that may be measured are layer thickness, strength (such as California bearing ratio, k, or modulus of rupture), layer material response (elastic modulus), or perhaps some response of the total pavement system (such as surface deflection or dynamic stiffness modulus).

For airport pavements, a structural evaluation is important because it provides the input necessary for the following:

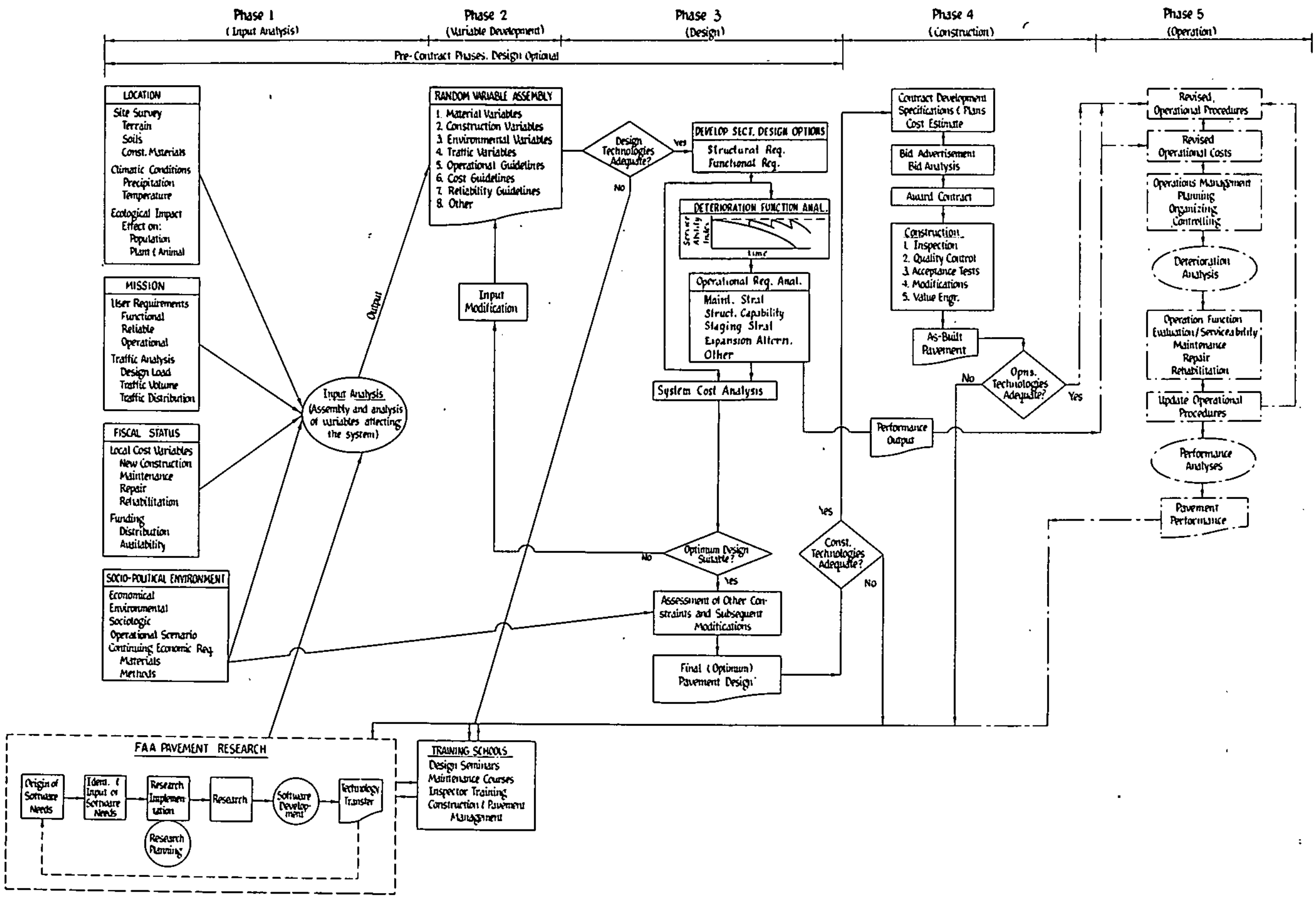
1. Determination of the allowable load that can use a specific pavement for a predetermined life,
2. Estimation of the remaining life of a pavement at a given time and aircraft-traffic history,
3. Assessment of the strength of existing pavements when strengthening or rehabilitation programs are being considered, and
4. Assessment of future overlay requirements to increase the strength of an existing pavement.

In structural evaluation studies, it is imperative that the in situ properties of all component pavement layers be ascertained. One obvious way of obtaining this information is to perform direct sampling or destructive testing of the pavement system. However, recent research has focused considerable attention on the use of nondestructive testing (NDT). Such methods have obvious potential advantages over destructive testing that include both direct (the testing itself) and indirect (user and delay) cost savings, simplicity, and speed. The indirect advantages are particularly important because they allow more extensive test coverage of the pavement and increase the reliability of the data obtained.

At present, NDT research is focused on two major areas. They are

1. Evaluation of the total pavement system response to dynamic loads and
2. Evaluation of the elastic-layer properties

Figure 1. Pavement system framework.



of the component layers.

Included in the first category are vibratory tests that measure either the dynamic deflection basin of the pavement surface at a given load (i.e., constant-load devices) or variable-load vibrators that characterize the total behavior of the pavement system. In dynamic evaluation, the plate load is proportional to the dynamic deflection. The slope of this load-pavement deflection response (i.e., the dynamic stiffness modulus) is conceptually identical to the static k term used in rigid pavement analysis (i.e., the modulus of reaction). This topic is discussed in detail in a paper by Hall in this Special Report.

Nondestructive evaluation techniques used to determine the elastic modulus of component layers have progressed on two fronts. One approach is the use of dynamic deflections obtained from testing in combination with theoretical elastic-layer models. The method is a trial-and-error procedure that evaluates an unknown modulus of one layer (i.e., the subgrade or base) so that the predicted (theoretical) deflection matches the observed dynamic deflection. The other type of approach uses widely known techniques of wave propagation through an assumed elastic medium. This concept uses the mathematical relation between wave velocity and shear (elastic) modulus. Both of these approaches are promising, but the important role of the known nonlinear (stress-dependent) characteristics of both fine-grained and granular materials must not be neglected in the interpretation of the results obtained. Thus, even when NDT techniques become truly refined, the concurrent use of at least limited destructive testing should be continued.

In contrast to structural evaluation, condition or performance surveys have as their major object the monitoring of the state of deterioration of the pavement at a specific time. Periodic surveys provide a time history of the pavement deterioration function (i.e., the performance of the system). In condition surveys, the variables measured are similarly dependent on the ultimate use and design model employed. In general, the parameters measured reflect only surface conditions; generally, no attempt is made to explain the occurrence of any deterioration.

To be effective, routine condition surveys should include both structural and functional measurements. To be most effective, the survey should

1. Determine the presence, location, and, if possible, quantitative density (occurrences per unit length or area) of all noticeable pavement defects or types of distress present—both load and nonload associated,
2. Measure the pavement unevenness (roughness) by either profiling or other procedures, and
3. Measure the skid-resistance of the pavement system.

Many pavement agencies also regularly monitor pavement deflections as a routine part of the conditions survey, and this parameter may be very useful in assessing relative changes (i.e., determination) with time. Because the runway is a unique pavement area whose performance history must be evaluated primarily on functional characteristics, the importance of items 2 and 3 above should be obvious.

AIRPORT PAVEMENT SYSTEM

To place the problem of airport pavement design and performance in a better overall perspective, various systems-oriented frameworks for pavements have been developed. One such procedure, developed by the U.S. Army Corps of Engineers for the Federal Aviation Administration, is shown in Figure 1 (8). The detailed procedure and philosophy of this particular system will not be discussed here, but several comments regarding its application are relevant. The overall system approach is divided into five phases:

Phase	Description
1	Input analysis
2	Variable development
3	Design
4	Construction
5	Operation

Of especial relevance is that both evaluation and performance surveys are included as integral parts of the operation phase (phase 5). Also, the system provides feedback from the pavement performance phase (5) back to the design phase (3). This feedback is the most vital, but also the weakest, link in the overall pavement management scheme as generally practiced today. In particular, there are three important elements that are necessary for a successful systems approach. These are

1. Verification that the as-built pavement (phase 4) is indeed the final (optimum) pavement design shown in phase 3 (design),
2. Verification that the design values selected for input from phase 2 (variable development) into the design methodology used in phase 3 are indeed the actual levels the pavement in the operation phase (5) is being exposed to, and
3. Verification that the predicted performance output (phase 3) is indeed the actual pavement performance obtained in the operation phase.

Unless these feedback loops become an integral part of the overall pavement design and management scheme, the operation phase will simply act completely independent of the other four phases.

Verification: As-Built Pavement Structure

It can be stated with a high degree of confidence that the first verification procedure—that the as-built pavement structure is in accordance with the final recommended design structure—is indeed the case in most civil and military construction. In fact, by far the greatest effort in construction control is exerted on this facet by frequent inspection, quality control, and acceptance testing for thickness and material-quality effects of the pavement layers above the subgrades. Also, the intro-

Figure 2. Types of potential deviation of design value from actual value.

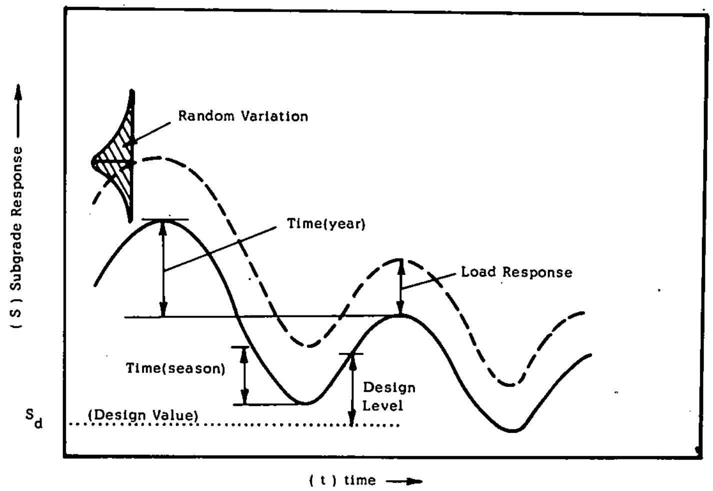


Figure 3. Resilient modulus of San Diego test road.

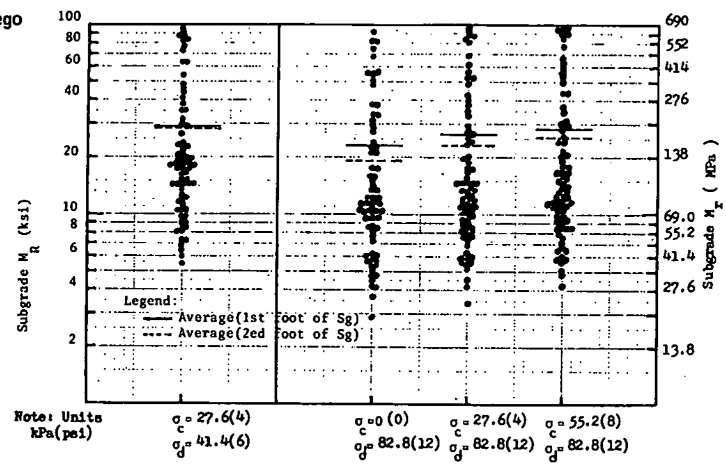


Figure 4. Comparison of load equivalency methods as function of gross load percentage.

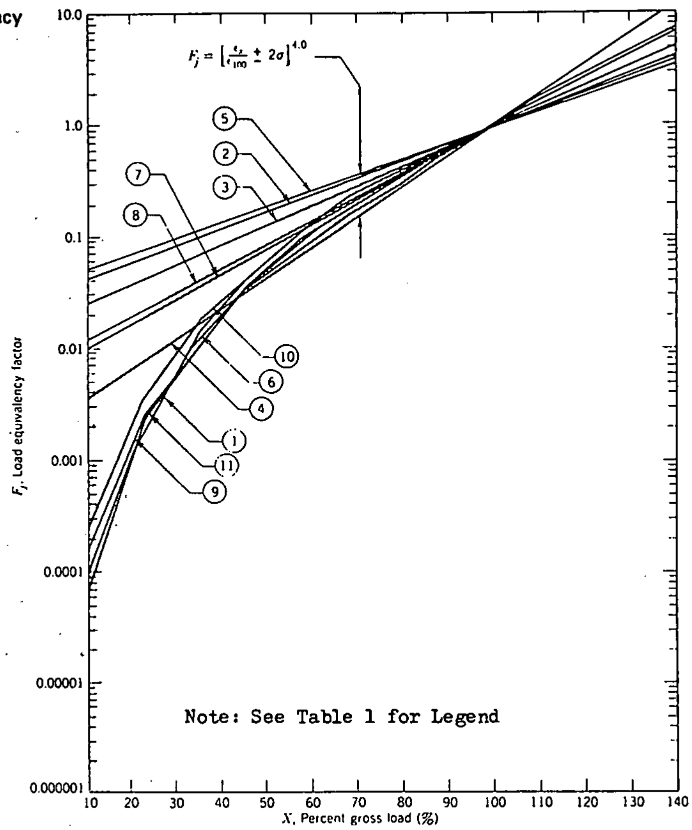


Table 1. Legend for Figure 4.

Type of Approach	Reference to Figure 4	Method	Base Load
Empirical equivalency	1	California	22.2-kN single wheel
	2	Kentucky	44.5-kN single axle
	3	Kentucky-American Association of State Highway Officials	80.0-kN single axle
	4	Kentucky (44.5-kN single axle/16)	80.0-kN single axle
	5	Painter	80.0-kN single axle or 143-kN tandem axle
	6	Corps of Engineers	80.0-kN single axle or 111-kN tandem axle
	7	Shook and Finn	80.0-kN single axle or 143-kN tandem axle
	8	Asphalt Institute (MS-1)	80.0-kN single axle or 143-kN tandem axle
	9	American Association of State Highway Officials (p_t = 2.0)	80.0-kN single axle or 143-kN tandem axle
	10	American Association of State Highway Officials (p_t = 2.5)	80.0-kN single axle or 143-kN tandem axle
Theoretical equivalency	11	Deacon	80.0-kN single axle or 143-kN tandem axle
	F_j limits	Asphalt Institute (MS-11)	72 different aircraft having range of 286 to 3840 kN

Note: 1 kN = 225 lbf.

duction of statistically based concepts in recognizing the inevitable variability associated with construction and inherent material properties, a topic that is discussed in detail in papers in this Special Report by E. Brown, R. Brown, and Wathen, is an improvement over previous control methodologies.

Verification: Design Input Variables

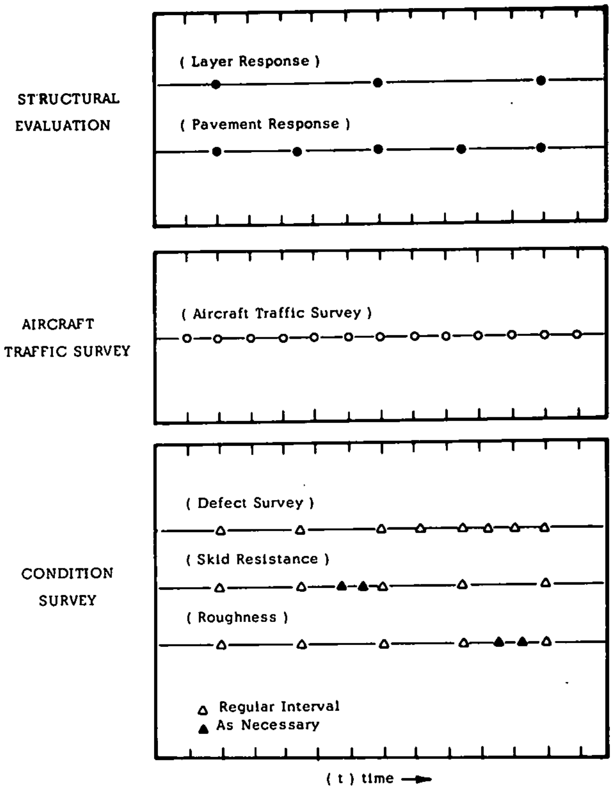
The design of an airport pavement structure, like that of any other pavement facility, must consider the effects of (a) subgrade soil, (b) traffic, (c) environmental conditions, (d) construction materials (above subgrade), and (e) economics. The evaluation of these parameters by using the concepts of the type of failure conditions selected constitute the design analysis. Obviously, all design procedures will provide a design pavement thickness given the design input values, such as subgrade response, traffic level, or design period. Although such a process may be termed design, the success or failure of the pavement design depends wholly on the engineering effort and qualitative engineering assessment that go into the selection of the design values.

Unfortunately, although almost all current design procedures treat each of the design parameters in a deterministic or constant sense, each input parameter has some degree of variation associated with its value. Thus, recent design improvements have begun to incorporate this variability as another input factor, which results in design procedures based on stochastic or statistical reliability concepts.

Without question, the underlying principle for verification of the design system is that the input variables used in the design process must be those occurring in the operational phase of the pavement system although deviations between design and actual conditions will always exist. These deviations may be categorized as

1. Random variations associated with construction or inherent in the materials;

Figure 5. Suggested performance-evaluation framework.



2. Time-dependent deviations that may be due to aging, environmental effects, or combinations of the two;
3. Deviations due to load-induced responses; and
4. Deviations or predictive errors between the assumed design level and that actually occurring.

To assist in visualizing these deviations, Figure 2 illustrates schematically a potential variation of subgrade response (i.e., strength or modulus) as a function of time. In this example, all possible types of deviations are present, but for other variables, one or more types of deviation may not be. Of particular interest relative to design and performance is the deviation between the design value and the actual mean response at any given time. In this example, the deviation in load response may be due, for example, to differences in the stress-dependent responses. To illustrate the possible magnitudes of some of these expected deviations, Figure 3 shows the actual variability found in resilient modulus tests of undisturbed samples of a supposedly uniform clay material under a variety of stress conditions after 7 years of traffic (13).

If a unique value of a parameter is used in the design model, conservative designs can be obtained by a judicious selection by the engineer who has evaluated all known considerations. However, increased accuracy, in this example, can be obtained by using predictions of the time-dependent response and stochastic concepts within the framework of a cumulative-damage analysis. Obviously, the overall verification must include (a) layer thicknesses, (b) material qualities, (c) environmental considerations, (d) subgrade conditions, and (e) traffic conditions.

As stated above, the first two are controlled in the construction procedure and hence are verified. The verification of environmental factors is developed from a study of previous climatic conditions and the knowledge of their effect on performance. The subgrade variable can be only indirectly verified during the construction process, i.e., by enforcement of the compaction specifications. However, even with compaction control, there may be potentially large differences between the actual and the design strength. The final factor, that relating to the effect of traffic, is seldom if ever verified for airport pavement design. It is unfortunate that among those variables affecting design and performance, the two most critical factors (subgrade and traffic) generally have the least degree of verification.

In the majority of airport pavement design methods, the effect of traffic is treated in a very cursory manner, usually by some estimate of the critical aircraft passes anticipated to use the facility. Generally, the effects of the traffic mixture are not even considered.

It is well established that pavements deteriorate progressively under traffic and that each load increases the finite distress and progressive damage to the pavement system. Highway pavement design methodologies have treated the combined destructive effects of the vehicle mixture by the use of equivalent-damage factors for over 20 years, and there is no potential reason for not introducing this technique of traffic analysis into airport pavement methodologies.

In addition to the factors considered in the analysis of highway traffic mixtures, the following input information is required for the development of a predictive airport traffic model:

1. The specific types of aircraft in the mixture,
2. The anticipated traffic volume of each aircraft within an analysis period,
3. The actual distributions of percentages of gross mass of given aircraft types,
4. The lateral distances between the aircraft centerlines and the centers of their main gears, and
5. The specific degree of lateral wander usually associated with a specific pavement area.

The incorporation of all these considerations into a predictive traffic-mixture model is given in several design procedures for full-depth asphalt pavements (17, 18, 19). These procedures are based on theoretical considerations of the equivalent-damage factor. Figure 4 and Table 1 (20, p. 154) show that there is good agreement between the theoretical concept and the empirically derived equivalency factors for loads common to both highway and airport pavements (20). The latest model, developed for the U.S. Navy, is a computerized version that gives as output the lateral distribution of equivalent F-14 aircraft strain repetitions laterally across a taxiway or runway pavement (19). The input variables are up to 300 combinations of types of aircraft [variable load, tire pressure, spacing, aircraft-to-main-gear center-to-center distance, and degree of wander (which is characterized by the standard deviation of the assumed wander of each specific aircraft type)].

Although there is no similar model for rigid pavement analysis, similar concepts can be applied to the development of solution techniques. The procedure is directly applicable to rigid pavements having wide slab widths or where the pavement can be analyzed without major violation of the assumption of a semi-infinite continuous layer. However, for small slabs (joint spacing), where the tensile-stress magnitude is a function of the distance from a joint or pavement edge, an added difficulty will arise.

Verification: Predicted Performance Output

The verification of the predicted performance output to the actual performance observed during the operation phase is the most difficult but most important verification step. In addition to the deviations of the as-built structure (probably minor) and of the selection of the design input variables (probably major), this verification analysis results in another deviation, i.e., the error introduced by the performance or design model itself. Thus, this verification should concern itself not only with structural performance, but also with functional criteria. In addition, it is possible that deviations in the design input variables will cancel each other out (e.g., a conservative estimate of strength could be balanced by an unconservative estimate of traffic).

The importance of obtaining a predicted-performance history similar to that observed is that it directly affects the economics, rehabilitation planning, existing load capacity, and remaining-life considerations.

SUGGESTED FRAMEWORK

A general conceptual framework for airport pavement evaluation is presented. The evaluation procedure should include surveys of (a) structural evaluation, (b) aircraft traffic, and (c) pavement conditions.

Each of these should be done at regular (periodic) intervals to obtain the optimum use of the data collection system. The structural-evaluation survey should have as its ultimate object the evaluation of layer and pavement response (i.e., strength, modulus, and deflection). The evaluation of the layer responses could be done at longer intervals, but at least the initial evaluation should use both destructive tests and field or laboratory tests. Deflection measurements (preferably dynamic) should be obtained at the same intervals as those recommended for the traffic and condition surveys.

The aircraft-traffic surveys can be made at any convenient time interval. Because this information is generally available from the airport administration, the major effort of this phase is the reduction of the information to a format that will be usable by the pavement engineer.

The condition surveys should be conducted at frequent intervals; the object of this operation should be to obtain information about the type and severity of visual pavement defects, the skid resistance of the pavement (runway), and either the profiling or measurement of the pavement roughness.

A general schematic illustrating these concepts is shown in Figure 5.

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Aircraft Pavement Loading: Static and Dynamic

R. C. O'Massey, Douglas Aircraft Company, McDonnell Douglas Corporation, Long Beach, California

The subject of pavement loading by aircraft is treated by presenting a series of tables and figures designed to cover the essentials of pavement loading through the various phases of aircraft operation. The phases include static, slow taxi, steady-state turns at various speeds and turn radii, takeoff roll, roughness, landing impact, and braking. Figures and tables that present DC-8 responses at a number of international airports are also included.

This paper presents information of two kinds: The first is that concerning pavement loading such as is published in National Aircraft Standard 3601 documents (1, 2, 3) and widely disseminated by all major aircraft companies, and the second is an attempt to show by selected tables and charts the answers to a wide range of questions that have been discussed over the years.

Aircraft overall performance, strength, and performance of functional components (such as landing gear, tires, and brakes) are subject to federal regulation, which leads to a natural tendency to present information by using aeronautical terminology [e.g., the airplane