ties of rigid pavement slabs, relations between deflection data and temperature, wave-velocity techniques for the determination of elastic properties, relations between deflection data and pavement performance, and effects of pavement overlays on vibrator results.

The mathematical model describing the nonlinear response of pavements can be used to predict the dynamic stiffness of a pavement given the loading conditions on the pavement directly under an aircraft wheel, to correlate the different values of dynamic stiffness measured by different vibrators at the same pavement location, and to predict the thickness and elastic moduli of each pavement layer in terms of the measured values of the dynamic stiffness for a series of load-plate sizes.

ACKNOWLEDGMENT

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Abridgment

Nondestructive Testing: Frequency Sweep

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A nondestructive testing (NDT) system was used to determine the physical conditions of existing pavement systems. The characteristics of the test were a static load of 71 kN (16 000 lbf) superimposed with a constant sinusoidal dynamic load and frequencies ranging from 5 to 80 Hz (the frequency sweep). For testing, a dynamic load of 17.8 to 53.4 kN (4000 to 12 000 lbf) could be selected. Each such test requires approximately 10 min and costs approximately $30 (a conventional plate-bearing test requires approximately 1.5 d and costs approximately $1500). The nondestructive nature and the rapidity of NDT minimize interference by the testing to aircraft operations, provide a better indication of the variations in the pavement support condition, and reduce the cost of testing.

The NDT procedures were standardized, the data were analyzed, and the results were used in pavement evaluation and functional design. Three subsystems in a computer system are used for the analysis, evaluation, and design. In the first subsystem, aircraft response is related to pavement smoothness, and the capacity of a pavement to withstand repeated aircraft loading is related to the user's requirements and demand forecast and to the need for maintenance. In the second subsystem, the required pavement thicknesses and composition are determined that meet the current and future requirements. In the third subsystem, the cost/benefit aspects of alternative pavement designs are evaluated to provide airport operators with realistic criteria for planning future pavement needs.

Before final adoption of the entire system of frequency-sweep NDT and its associated pavement evaluation and functional design procedures, a recommendation is made to conduct a validation program at four airports.

Abridgment

Nondestructive Testing of Flexible Pavements by Using Prototype Loads

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A major problem confronting persons concerned with the operation of airport pavements is that of evaluating existing systems. The requirements imposed by the rapid advance of air transportation and aircraft developments have outstripped evaluation techniques borrowed from highway engineers. The policy of closing traffic lanes to permit repairs on highways may have significant consequences when transferred to even a single runway of a major airport. The rate and magnitude of loadings imposed on airport pavements today have markedly increased failures and the consequent closing of runways (1) for repairs.

Technology must provide the hardware and methodology for evaluating existing pavements, for forecasting future situations and requirements, and for directing remedial measures. Operational restrictions require that procedures be developed that reduce to a minimum the closing of runways and their appurtenances, which thus precludes the use of destructive testing techniques such as test pits. Of additional importance is that destructive techniques are necessarily confined to relatively small areas of pavements, so that at best, they can provide diagnostics of only limited sample points and these at considerable cost and time.

The volume changes that can occur in response to ambient conditions can cause pavement surfaces to curl and warp. Hence, portions of the surface may not be in contact with the underlying material when subjected to im-

Figure 1. LED beam.

Figure 2. Mobile deflection measuring device.

EDGE OF WHEEL

1.8 Minimum

COUNTER-WEIGHT

BEAM

INITIAL PAVEMENT SURFACE

TO POWER AND RECORDING

DEFLECTED PAVEMENT SURFACE

BEAM

LVDT

PLUNGER

INITIAL PAVEMENT SURFACE

DEFLECTED PAVEMENT SURFACE

LVDT DETAIL

Note: 1 m = 3.3 ft.

BEAM

LED MODULE

DETECTOR

LENS

INITIAL PAVEMENT SURFACE

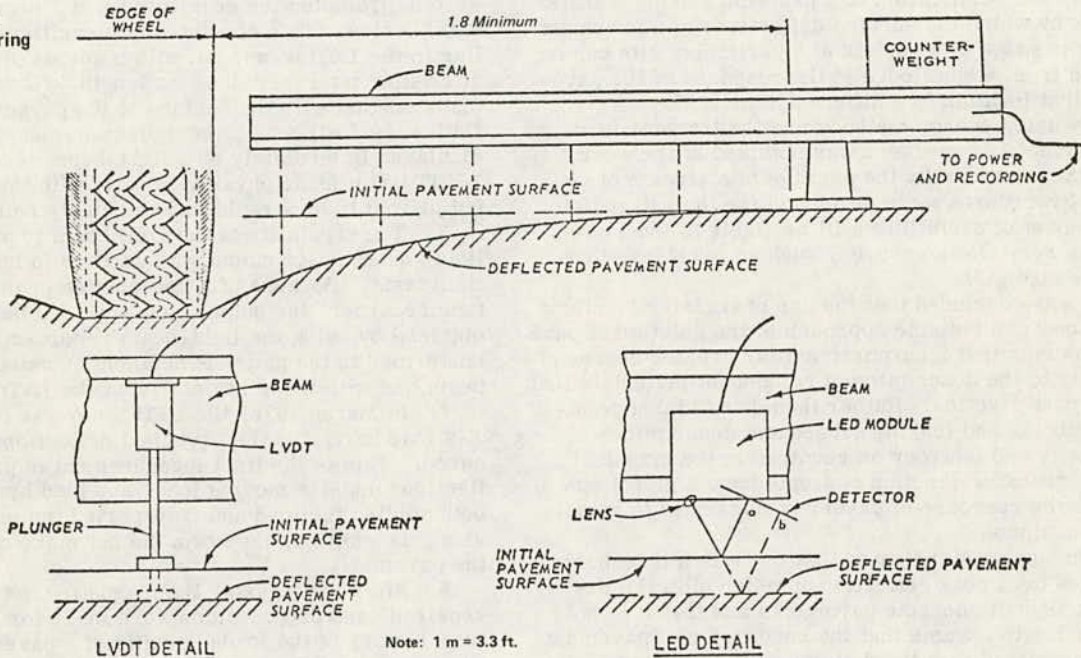DEFLECTED PAVEMENT SURFACE

LED DETAIL

Figure 3. LVDT beam and P-2 fire truck.

posed aircraft loadings. Consequently, any apparatus used to evaluate a pavement system should not alter the conditions prevailing before loading. The devices in use today, such as the Benkelman beam and vibrators, all suffer from this limitation. Briefly, the test procedure for the Benkelman beam involves positioning the beam next to a stationary load vehicle and then measuring the rebound of the pavement as the vehicle moves away. Vibrators, of necessity, must seat the pavement before introducing safety-state vibrations, and the nature of their loading (magnitude and frequency) has little resemblance to the transient input of actual aircraft. Although Benkelman beams treat vehicular loads, they monitor only residual deflections after the pavement surface has been seated and for vehicles at creep speeds.

Needless to say, to gain widespread acceptance and use, new hardware must be (a) inexpensive; (b) operable with minimal (or no) training on the part of the user; (c) lightweight, self-contained, and mobile; and (d) able to accommodate the vehicles (or aircraft) on hand at facilities.

DISCUSSION OF RESEARCH

In November 1970, a research project at the School of
Civil Engineering at Purdue University was begun that
sought to exploit the concept of transfer functions to pre-
dict pavement deflections caused by moving aircraft, and
in October 1971, it was extended to the examination of
the time-dependent relations between the energy imparted
to a pavement by aircraft and the condition of the pave-
ment system. The field investigations were conducted
at Kirtland Air Force Base, Albuquerque. Time-
dependent deflection-response functions were measured
with specially designed deflection gauges using linear
variable differential transformer (LVDT) displacement
transducers. The overall system was designed to simul-
taneously monitor the vertical movement of a pavement
at six different locations on a line normal to an aircraft's
path. The prototype investigations were conducted at
three different cross sections. Four prime movers were
used at each test site—the C-135, C-131, and C-130
military aircraft and a specially designed (F-4) load
cart. The following results were obtained:

1. The state of the art was advanced by the develop-
ment and field verification of a procedure using transfer
functions by which the surface deflections of a pavement
after the passage of a vehicle at a particular site can be
predicted from a knowledge of the response of the pave-
ment at that location to a different vehicle (2).
2. By using energy methods and the transfer func-
tions developed, a measure was obtained of the work
done to the pavement by the passage of a stream of ve-
hicles. Procedures were developed for the estimation
of the amount of useful life still available to the system
and of the remedial measures, such as overlays, that
should be taken (3).
3. It was concluded that the use of transfer functions
offers a new and reliable approach to the solution of pave-
ment problems that incorporates a far greater degree of
versatility to the description of component materials than
does current practice. Rather than determining point-
wise attributes and making subsequent assumptions of
homogeneity and isotropy as required in the classical
theories, transfer-function concepts have a global ap-
proach to the response of pavement materials to actual
aircraft loadings.
4. The analyses indicated that there is a threshold
cumulative total peak deflection at which distress de-
velops in asphalt concrete pavements and that it is not
unreasonable to assume that the condition of a pavement
can be correlated with the deflection that it has under-
gone. The field testing provided insight into the effect
of the thickness of overlays on the energy imparted to a
pavement and has led to the development of a procedure
for the determination of the thickness of an overlay so
that the pavement will perform satisfactorily under an
anticipated traffic volume.

After the concepts of transfer functions and an energy-
related distress criterion had been verified at the three
LVDT installations, the next phase of the research was
directed toward developing a breadboard model on a
mobile pavement-deflection measuring system. This
type of system obviates the need for the installation of
difficult and expensive built-in LVDTs. In addition, it
extends the evaluation to an entire runway-taxiway
(global) system from the single transverse line of em-
bedded gauges (local). The concept of the measuring
system was to move the length of the pavement and in
transit compile the inherent transfer functions and their
characteristics. A secondary object was to provide the
capability of rapidly defining the time history of the

loaded pavement under moving aircraft. The develop-
ment of the equipment for measuring the pavement de-
flection was based on a study of runway-deformation
contouring by using holographic techniques. The devel-
opment of the mobile device was based on the observa-
tion that a point on the surface of a pavement 1.8 m (6 ft)
lateral from the edge of an aircraft wheel showed no
measurable deflection. Consequently, attention was di-
rected toward the construction of a cantilever beam that
would span this distance and provide a horizontal datum
from which vertical deflections could be measured. The
following procedures were used:

1. A beam was constructed that uses light-emitting
diodes (LED) to reflect coherent light from the pavement
onto detectors (Figure 1). Then as the pavement de-
flects, the reflected light will register differently on the
detector (as shown in Figure 2). The calibration of the
beam provides a scale that relates the differences ob-
tained on the detector to the vertical displacements. No
physical contact is required between the beam and the
pavement at points of measurement. The data were
stored on a magnetic tape recording system.
2. Early difficulties with the electronics of the LED
system prompted the development of a secondary (fail-
safe) device. This consisted of a cantilever beam sim-
ilar to the LED beam, but with a series of LVDTs spaced
at regular intervals along its length, whose plungers
made contact with the surface of the pavement (Figure 3).
Unlike the LED beam, the deflection measurements were
displayed immediately on a light-beam recorder. The
LVDT beam made physical contact with the pavement,
but proved to be a rapid and extremely reliable device.
3. The capability of the LED beam to provide re-
liable quantitative output was verified in laboratory and
field tests. Because of a malfunction of the magnetic
tape recorder, the output from the LED beam had to be
obtained by using the light-beam recorder. The results
conformed to the patterns obtained by using the LVDT
beam and with those registered at the LVDT gauges.
4. In March 1976, the LED beam was mounted on an
F-4 load cart, and the pavement deflections were mea-
sured. This is the first measurement of pavement de-
flections under a moving load, obtained by a vehicle that
both applied the load and transported the measuring de-
vice. In addition, the beam did not make contact with
the pavement.
5. After these tests, the magnetic tape recorder was
repaired, and preparations were made for obtaining the
time history of the loaded profile of a pavement under a
moving aircraft loading. This was accomplished in June
1976. The LED beam was mounted on the F-4 load cart,
and deflection measurements were obtained for more
than 605 m (2000 ft) of taxiway and 2000 m (1.25 miles)
of runway—all in less than 3 h (including the time taken
because of damage to a gauge that then required extra
calibrations).

SUMMARY AND CONCLUSION

A breadboard model of a nondestructive, noncontact,
rapid, mobile, global device for measuring the response
of pavements to moving aircraft has been developed and
tested under field conditions.

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Abridgment

Pavement Evaluation With the Falling-Weight Deflectometer

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The falling-weight deflectometer (FWD) is a reliable, simple, and yet effective tool to determine the structural properties of pavements for roads and runways. Its characteristics of level of force (up to 60 kN) and loading time (approximately 30 ms) are more representative of heavy traffic than are those of most other deflection equipment. The deflection of the pavement and the deflection bowl are determined by geophones (velocity transducers) in the center of the loaded area and at certain distances from the center. The deflection levels are not affected adversely by the configuration of loading or the recording system, nor by possible influences of unstable reference points such as are encountered with some alternative systems.

A comprehensive description of the method has been published elsewhere (1). The principles are as follows:

The pavement structure is represented by a multilayer linear elastic system in which the materials are homogeneous and isotropic and are characterized by Young's modulus of elasticity (E) and Poisson's ratio (ν). In most cases, the structure can be regarded as a three-layer system (Figure 1) consisting of a bound top layer (E_1, ν_1, and thickness h_1), an unbound or cemented base layer (E_2, ν_2, and h_2), and a subgrade (E_3, ν_3, and infinite thickness). To simplify the system, fixed values are adopted for ν for all layers. The test load is assumed to be uniformly distributed over one or more circular areas.

The response of the pavement to a test load is characterized by the maximum deflection and the shape of the deflection bowl. The latter parameter is characterized by the ratio (Q_r) of the deflection at a distance r from the load (δ_r) to the deflection under the center of the test load (δ_0); i.e., $Q_r = \delta_r/\delta_0$. The ratio Q_r was chosen rather than the radius of curvature because Q_r can be measured more easily with existing equipment and provides equivalent information. The distance r can be fixed depending on the type of structure and is preferably such that Q_r is approximately 0.5 (2).

By using the BISAR program, graphs have been prepared giving the relations among E_1, δ_0, Q_r, and h_1 for predetermined values of E_2, h_2, E_3, and r for a given test load. From such graphs, with δ_0 and Q_r measured, two unknown structural parameters of the pavement can be determined if the other variables are known or can be estimated.

The pulse load is applied by a mass falling onto a set of springs that are mounted on a rigid circular plate resting on the pavement surface. Extensive tests with a prototype have shown the suitability of the method for determining the shape of the deflection bowl (1).

For routine measurements, a commercially available FWD was used. This FWD is mounted on a small trailer that can be towed by an automobile. The falling mass weighs 150 kg, and the maximum force developed is 60 kN at a drop height of 400 mm and a pulse width of 28 ms. These values were almost independent of type of pavement structure. The diameter of the foot plate is 300 mm.

The deflection of the pavement is measured by velocity transducers (geophones), one in the center of the loaded area and one or two at a fixed distance from the load. The transducers (50 mm in diameter and 55 mm in height) operate over a frequency range of 1 to 300 Hz. They are very rugged, which is advantageous in field conditions.

The FWD and the trailer were modified to permit quick operation with remote control from the towing car to enable measurements to be made in or between the wheel tracks without changing the line of drive. The trailer accommodates the power supply, and the recording instruments are in the automobile.

By using this equipment, surface deflections can be measured accurately and easily without the problems (such as the measuring reference points being located in the deflection bowl) that are encountered with some alternatives. The FWD is shown in Figure 2.

The transducer signals used to record the deflections are displayed on a screen to permit the operator to quickly verify the correct operation of the equipment and instruments. The maximum values of the deflections are digitized and stored on a tape recorder via a data unit or can be tabulated by a printer. The location of the points at which deflections are measured is recorded both longitudinally and transversely (in or between the wheel tracks or other position) with respect to the geometry of the road. A desk calculator facilitates the introduction of temperature data and is also used to calculate deflection ratios, mean values, variances, and other statistical data. A chart recorder is used to display the readings and calculated results.

Most pavement structures exhibit nonlinear behavior, particularly at low force levels, but generally, at force levels >30 kN, there is a straight line relation between deflection and force (Figure 3) (2). Thus, extrapolation of the deflection values to very heavy loads such as those under aircraft can be made with reasonable accuracy from measurements at, for example, 30 and 60 kN.

The residual life is the difference between the original design life of the pavement and the life already used. Because the initial decrease in asphalt modulus is relatively small, the design life of a pavement can be determined from the layer thicknesses and moduli derived from deflection measurements by using a Shell design chart (such as Figure 4) for the relevant subgrade modulus, weighted mean annual air temperature, and type of asphalt mix (3) (the same type of mix, of course, as anticipated with the interpretation) and deriving the number of standard axle-load applications for the given values of h_1 and h_2. Depending on the difference between the de-