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NONDESTRUCTIVE PAVEMENT EVALUATION

B. M. DAS
AIR FORCE CIVIL ENGINEERING CENTER
DIRECTORATE OF ENGINEERING MATERIALS

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CIVIL AND ENVIRONMENTAL
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Research has been in progress for about 10 years to develop a compatible pavement evaluation procedure for airfields based on nondestructive tests. A successful nondestructive pavement evaluation technique will reduce the time of closure of various airfield facilities needed to conduct destructive tests required for conventional pavement evaluation.

This study provides a comparison of the projected pavement life of several

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airfield features estimated by nondestructive and destructive pavement evaluation procedures. For aircraft and gross loads on similar pavement sections, the nondestructive evaluation procedure yields higher numbers of allowable operations as compared to that obtained by the destructive test evaluation technique at this point in the research effort. Follow-on research is planned which will cause the two evaluation procedures to yield more closely compatible numbers.

PREFACE

This report was prepared by the Air Force Civil Engineering Center (AFCEC), Tyndall Air Force Base, Florida, under job order 20544P07. The report summarizes work done between October 1976 and September 1977. While the report was written by Dr. B. M. Das during his summer faculty assignment, the analysis represents work done by both the author and the project engineer, Lt Col George D. Ballentine. The numbers of aircraft operations which are projected as allowable by the nondestructive evaluation system and reported as such in this document represent the results of analysis procedures developed up to the point of publication of this paper. Work is continuing on the development of the nondestructive evaluation system, and it is expected future results will yield numbers more closely compatible with the destructive evaluation system.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS) where it will be available to the general public including foreign nations.

This technical report has been reviewed and is approved for publication for record purposes only. Opinions expressed represent those of the author and not the official position of the Air Force.

Joseph S. Pizzuto

JOSEPH S. PIZZUTO, Colonel, USAF, BSC
Commander

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION I

INTRODUCTION

One of the important responsibilities of the Air Force Civil Engineering Center is to evaluate the load carrying capacity and the remaining service life of airfield pavements. The pavement evaluation procedure presently adopted requires destructive testing. This requires the closure of runways and taxiways for extended periods of time for completion of field tests and collection of samples for laboratory testing.

To improve the airfield pavement evaluation technique, the Air Force has been involved in developing a compatible nondestructive test procedure since 1967. The essence of this program is based on determination of the elastic properties; i.e., shear modulus and Young's modulus of each of the layers which constitute a given pavement section by means of vibratory testing. Subsequently, by using these results a computerized structural analysis is made to determine the allowable number of pre-failure operations for a given aircraft on that section of the airfield pavement. A historical review of the nondestructive pavement evaluation procedure has been presented by Nielsen and Baird (Reference 1). The present state-of-the-art for this technique has reached a considerable degree of sophistication.

The purpose of the present study is to compare the projected pavement life of various features of some airfields obtained from the analysis of destructive tests with that obtained from the analysis of nondestructive tests.

SECTION II

PAVEMENT EVALUATION PROCEDURE BASED ON DESTRUCTIVE TESTS

This is the present technique for evaluation of the allowable gross loadings (AGL) for airfield pavement features. The procedures for evaluation of flexible and rigid pavements are given in References 2 and 3 respectively. For evaluation purposes, various aircraft are placed under a number of group indices (GI) as shown in Table 1. This classification is based on the number of wheels, gear configuration, and tire contact areas of the aircraft. For any given airfield feature, the pavement evaluation study yields an estimate of the allowable gross load for each of the group indices under capacity, full, minimum, and emergency operational categories. The operation categories mentioned above are based on the coverage levels given in Table 2. By definition, a coverage is said to occur when all points of the pavement surface have been subjected to one application of stress by the design aircraft.

The important field results needed for determination of AGLs for a given section of airfield are:

1. Flexible pavement
   a. Thickness of each layer constituting the pavement section
   b. CBR values of all soil layers
2. Rigid pavement
   a. Thickness of the layers of the pavement section
   b. Flexural strength of Portland cement concrete.
   c. The modulus of subgrade reaction.

TABLE 1. AIRCRAFT GROUP INDICES *

SINGLE WHEEL			MULTIPLE WHEEL								
TRICYCLE			TRICYCLE						BICYCLE	TRICYCLE	DOUBLE TRICYCLE
1	2	3	4	5	6	7	8	9	10	11	12
C-123	A-7	F-111	C-7	C-130	EC-121		C-135	C-5	B-52	B-1	E-4A
	A-10	FB-111	C-9		KC-97		C-141				
	EB-57		C-54				E-3A				
	F-4		C-131				KC-135				
	F-5		C-140				VC-137				
	F-15		T-29								
	F-16		T-43								
	F-100										
	F-101										
	F-102										
	F-105										
	F-106										
	T-33										
	T-38										
	T-39										

* *Based on groupings* in use at the time of report preparation; groupings have since been somewhat revised.

TABLE 2. COVERAGES FOR VARIOUS AIRCRAFT OPERATION CATEGORIES

Operation Category	Number of Coverages	
	Channelized Section	Nonchannelized Section
Capacity *	25,000 for all aircraft except B-52; 10,000 for B-52	5000
Full	5000	1000
Minimum	1000	200
Emergency	200	40

* Capacity is defined as unlimited traffic. For computational purposes in this report, minimum values have been used.

SECTION III

PAVEMENT EVALUATION PROCEDURE BASED ON NONDESTRUCTIVE TESTS

The nondestructive pavement tests used for evaluation were conducted with equipment developed at the Civil Engineering Research Facility, University of New Mexico. All the components of the test equipment are placed in a van 8 feet wide and 35 feet long. For the nondestructive tests, a dynamic load of 1000 pounds which can be varied sinusoidally is applied by a vibrator on the surface of the pavement and frequency sweep between 10 and 3500 hertz is conducted. The vertical acceleration of the pavement at selected distances from the applied load is measured by accelerometers epoxied to the surface of the pavement. A phase computer is used to determine the phase angle from the signals recorded between accelerometers.

The phase angle/frequency plots obtained from field tests are then reduced to obtain plots of wave length against phase velocity which are referred to as the dispersion curves. The relations for the wavelength and phase velocity are as follows:

$$\lambda = \frac{360d}{\phi} \quad (1)$$

$$v = f\,\lambda \quad (2)$$

where

d = distance between the compared accelerometers (ft)

ϕ = phase angle (deg)

f = frequency (Hz)

λ = wavelength (ft)

v = phase velocity (ft/sec)

This dispersion curve can be obtained by the use of a computer program, NDTPLOT, which does the calculation of the values of λ and the corresponding v and completes plotting of the dispersion curve.

The peak wave velocity obtained from the dispersion curve gives the Rayleigh wave velocity, V_R, for the surface layer. The shear wave velocities in the underlying layers (i.e., base/subbase, subgrade) are obtained from the ordinates corresponding to the break points of the curve. The shear wave velocity, V_S, of the surface layer can be determined from the relation

$$V_S = \frac{V_R}{a} \quad (3)$$

where the ratio of V_R to V_S, a, is a function of Poisson's ratio, ν, of the material and its theoretical values are:

$a = 0.875$ for $\nu = 0$ and

$a = 0.955$ for $\nu = 0.5$.

Making linear interpolation, the following values have been determined for calculations in this study:

$a = 0.899$ for pavements with concrete surface layer and

$a = 0.911$ for pavements with asphaltic concrete surface layer.

With the shear wave velocities known, the Young's modulus for each layer of a given pavement section can be determined from the following theoretical relations:

$$G = \frac{V_s^2}{144} \frac{\gamma}{g} \tag{4}$$

$$E = 2 (1 + \nu) G \tag{5}$$

with ν = Poisson's ratio

G = shear modulus of the layer (lb/in^2)

E = Young's modulus of the layer (lb/in^2)

g = acceleration due to gravity = 32.2 ft/sec^2

V_s = shear wave velocity (ft/sec)

γ = unit weight of the material in the layer (lb/ft^3)

The average approximate values of γ and ν for different materials encountered in an airfield pavement section are given in Table 3.

TABLE 3. ASSUMED VALUES OF UNIT WEIGHT AND POISSON'S RATIO

Material	γ (lb/ft^3)	ν
Concrete	145	0.15
Asphalt	145	0.43
Base Course	120	0.25
Subgrade	110	0.43

Reference 1 states that the Young's moduli obtained from the above calculations yield somewhat higher values for asphaltic concrete surface layers, base/subbase layers, and subgrades. Hence, for actual pavement performance evaluation, corrections are made to obtain representative values of E. The present recommended correction procedure (Reference 1) is given in Table 4.

TABLE 4. CORRECTED YOUNG'S MODULUS (E_{cor})

Layer	E_{cor}
<u>Surface</u>	
Concrete	$E_{(concrete)}$
Asphaltic concrete	$\frac{E_{(asphalt)}}{2}$
<u>Base/Subbase with</u>	
Concrete Surface	$\frac{E^2\ (base/subbase)}{E_{(concrete)}}$
AC Surface	$\frac{E_{(base/subbase)}}{2}$
AC/concrete surface	$\frac{E_{(base/subbase)}}{2}$
<u>Subgrade with</u>	
Concrete Surface	$\frac{E_{(subgrade)}}{2}$
AC Surface	$\frac{E_{(subgrade)}}{2}$
AC/PCC Surface	$\frac{E_{(subgrade)}}{2}$

Note: $E_{(concrete)}$, $E_{(asphalt)}$, $E_{(base)}$, $E_{(subgrade)}$, correspond to Young's moduli of the materials represented in the subscripts obtained by using equation (5).

Ultimately, with the above calculations completed, the pavement evaluation is made by a computer program known as PREDICT. It is a non-linear finite element program which performs the structural analysis of the pavements in which the aircraft wheel loads are represented by Fourier Series and is capable of treating single and multiwheel landing gears. In order to obtain the number of passes that an aircraft can operate on a given pavement section before fatigue failure occurs, the following are used as input to the PREDICT code:

1. Name of the aircraft (at the present time, the aircraft in PREDICT code are B-1, B-52, B-57, Boeing 747, C-5, C-9A, C-130, C-141, F-15, F-16, F-105, F-111, FB-111A, KC-97, KC-135, and T-39)

2. Number of layers in the pavement section

3. Thickness, T, of surface layer, base course, subbase (if present) and subgrade. The thickness of subgrade is given by:

$$T_{subgrade} \text{ (in)} = 144 \text{ in} - T_{(surface + base + subbase)} \text{ (in)} \tag{6}$$

4. E_{cor} for all the layers

5. Tensile strength of concrete layer, t (in psi) (applicable to PCC pavement only)

6. Poisson's ratio for each layer

7. Degree of saturation, S_r, for the soil layers

8. Void ratio, e, for the soil layers

9. Plasticity index, PI, for the soil layers

10. Nature of traffic on the pavement; i.e., channelized or non-channelized.

The failure criteria used for the destructive test evaluation theory are not the same as those used for the nondestructive test pavement evaluation procedure. For PCC pavement, the criteria used for destructive tests are based on the development of the first crack in the pavement and are derived from large scale field tests conducted over the years. For nondestructive tests, the failure criteria for an AC wearing course is based on tensile strain; for a PCC wearing course on tensile stress; for subgrade on vertical compressive strain (Reference 1).

SECTION IV

PROCEDURE FOR COMPARISON OF PROJECTED PAVEMENT LIFE BASED ON DESTRUCTIVE TESTS TO THAT BASED ON NONDESTRUCTIVE TESTS

In order to make a reasonable comparison to see how well the projected pavement life based on destructive tests compares with that based on nondestructive tests, the following procedure has been adopted in this study. It is presented in a step-by-step manner for easier understanding. All comparisons presented here are made for capacity category operation of aircraft.

1. Review the AGLs for a given feature of an airfield for capacity category operation obtained in the pavement evaluation report based on destructive tests.

2. Determine the group indexes (GI) of the aircraft.

3. Compare the maximum gross load (Table 5) of an aircraft considered in step 2 with the AGL obtained for its corresponding GI in step 1. If the maximum gross load of an aircraft is less than or equal to the AGL for the corresponding GI, it may be selected as a case for the comparison study.

4. For an aircraft selected in step 3, determine the number of permissible operations at the AGL predicted by the destructive evaluation technique, using this relationship:

$$\text{No. of operations} = \underset{\substack{\uparrow \\ \text{Table 2}}}{\begin{array}{c}\text{No. of coverages for} \\ \text{Capacity Category}\end{array}} \times \underset{\substack{\uparrow \\ \text{Table 5}}}{\frac{P}{C}} \qquad (7)$$

${}^{P}/_{C}$ = pass-per-coverage ratio

5. Determine the values of E for various layers of the pavement (for the feature under consideration) from nondestructive test(s). If more than one test has been conducted in that feature of the airfield, the moduli can be calculated from representative values of V_s for the layers.

6. Correct the values of E obtained in step 5 by using Table 4.

7. Determine the tensile strength, t, of the concrete layer (if present) from tensile splitting tests of concrete cores.

TABLE 5. GROSS WEIGHT, MAIN GEAR WHEEL LOAD AND PASS-PER-COVERAGE RATIO FOR SOME AIRCRAFT

Aircraft	Maximum Takeoff Gross Weight[a] (KIPS)	Maximum Main Gear Wheel Load[a] (KIPS)	P/C[b]	
			Channelized	Nonchannelized
B-52H	488.0	67.1	1.63	2.0
B-57B	58.8	27.7	6.47	12.83
C-5A	769.0	30.2	0.81[c]	1.10[c]
C-130E	175.0	41.9	2.09[c]	4.05[c]
C-141A	316.6	37.4	1.72[c]	3.17[c]
F-105F	54.6	23.4	10.9	21.9
F-111A	98.6	47.0	4.92	9.8
KC-97G	187.0	44.5	3.41	6.11
KC-135A	300.8	35.5	1.68[c]	3.03[c]

[a] Reference 4.

[b] Reference 5.

[c] Pass-per-coverage ratio for rigid pavement is equal to twice the value shown.

8. Determine the main gear wheel load, WLOAD, for the aircraft by using the relation

$$\text{WLOAD} = \frac{\text{AGL}}{\underbrace{\text{(Max gross load of aircraft)}}_{\text{Table 5}}} \times \underbrace{\text{(Max main gear wheel load)}}_{\text{Table 5}}$$

9. Input the following to the program, PREDICT.

Name of aircraft

Nature of traffic (channelized or nonchannelized)

WLOAD (step 8)

t (step 7)

Number of pavement layers

Poisson's ratio for each layer (Table 3)

Plasticity index (PI) for each soil layer

Void ratio, e, for each soil layer (actual value if known or about 0.22 for base course and 0.45 for subgrade)

Degree of saturation, S_r, for each soil layer (actual value if known or about 80 percent)

10. PREDICT gives the number of allowable passes for the aircraft on the pavement section.

The number of passes obtained in step 10 by the nondestructive evaluation technique can now be compared with the number of passes obtained in step 4 by the destructive evaluation technique. It may be noted that the number of passes obtained by the above two methods are for the same aircraft and gross load.

A flow chart for the comparison procedure (steps 4 through 10) is given in Figure 1.

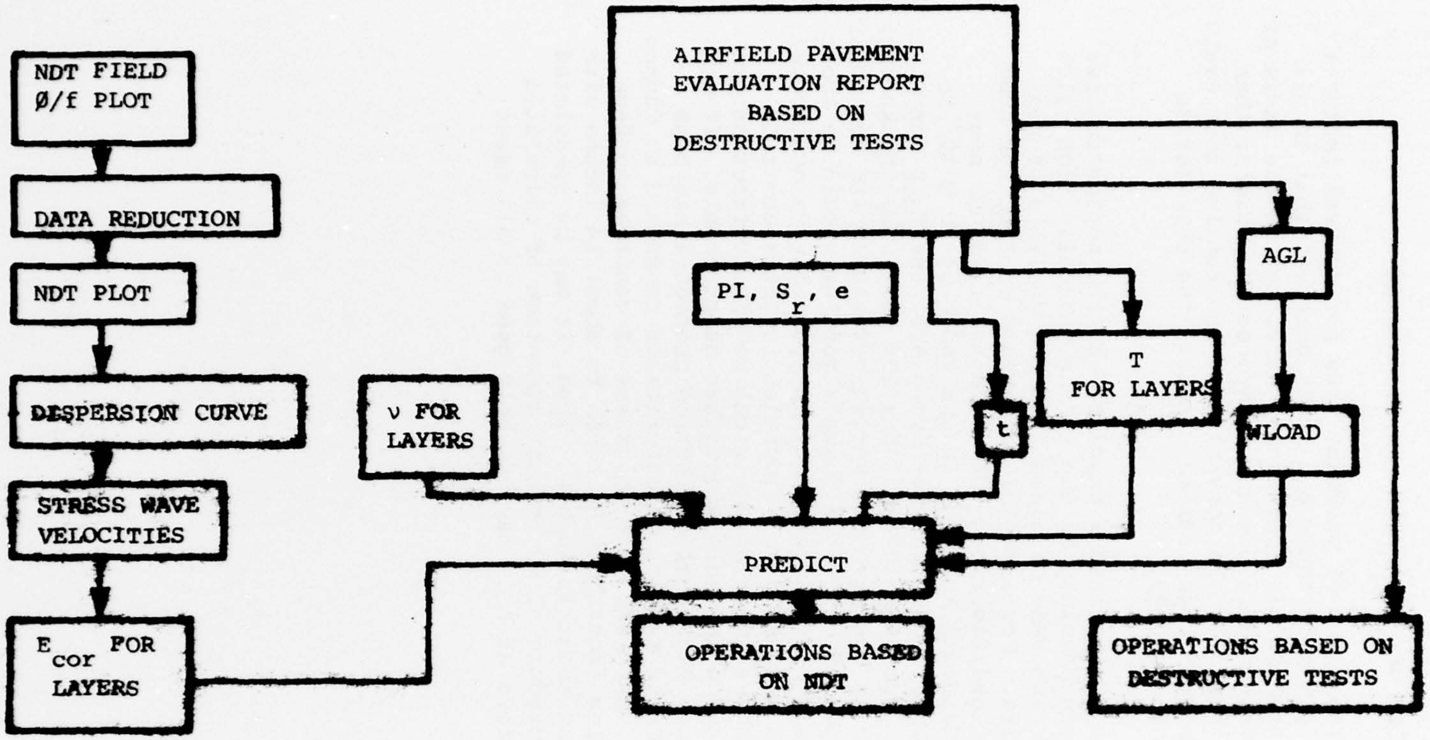

Figure 1. **Flow Chart for Comparison of Pavement Life Based on Destructive Tests to That Based on Nondestructive Tests.**

SECTION V

RESULTS OF COMPARISON AND DISCUSSION

The results of comparison of pavement life for several features of four airfields are given in Table 6. It is observed that in all cases, the number of permissible operations calculated on the basis of nondestructive test evaluation procedure is appreciably higher than that predicted on the basis of the conventional destructive test evaluation procedure. Based on these limited results, the correlation coefficient was found to be 0.29.

The higher number of operations predicted by the nondestructive evaluation procedure can possibly be due to the unusually high value of V_s and thus E_{cor} for subgrade obtained from the analysis of nondestructive test results. For example, the values of E_{cor} for subgrades (unified soil classification - CL) obtained from the nondestructive tests of Carswell AFB were in the range of 20×10^3 to 120×10^3 psi. Similarly in the case of Dyess AFB, the E_{cor} for CL type subgrades ranged from 55×10^3 to 135×10^3 psi. The thicknesses of the concrete layers in the pavement varied between 15 and 26 inches. However, the usual range of corrected Young's modulus should be about 3×10^3 to 10×10^3 psi. This discrepancy can possibly be attributed to the dominance of the stress wave velocities in thick concrete layers. This makes the validity of empirical modulus correction procedures of subgrades given in Table 4 somewhat questionable. It may be pointed out the above empirical correction procedure has been developed from the limited results of experiments conducted at Cannon AFB, New Mexico. At Cannon AFB, the thickness of concrete surface layer of pavement varies from about 8 inches to about 14 inches with an average thickness of about 11 inches. Thus, it may be speculated that the empirical procedure of 50 percent reduction of calculated Young's modulus to arrive at E_{cor} may not hold good in all cases.

TABLE 6. RESULTS OF COMPARISON STUDY

Air Force Base	Feature	Aircraft	GI	AGL (KIPS)	Operations Calculated from	
					Nondestructive test results	Destructive test results
Carswell AFB	R2B	B-52	10	330	815,000	16,300
	T9C	B-52	10	295	1,000,000	10,000
	R4C	B-52	10	420	1,000,000	10,000
	A3B	KC-135	8	215	1,515,000	15,150
Dyess AFB	A5B	B-52	10	290	200,000	10,000
	R1A	B-52	10	350	163,000	16,300
	T9A	B-52	10	475	163,000	16,300
	R6C	B-52	10	415	200,000	10,000
Keesler AFB	R1A	C-141	8	225	344,000	86,000
	R4B	C-141	8	265	344,000	86,000

TABLE 6. RESULTS OF COMPARISON STUDY (CONCLUDED)

Air Force Base	Feature	Aircraft	GI	AGL (KIPS)	Operations Calculated from	
					Nondestructive test results	Destructive test results
Davis Monthan AFB	R1A	KC-97	6	150	341,000	85,250
	R1A	KC-135	8	280	336,000	84,000
	R1A	B-52	10	230	163,000	16,300
	R2A	F-105	2	40	1,296,427	272,500
	R2A	F-111	3	80	520,857	123,000
	R2A	B-52	10	355	35,980	16,300
	R3A	F-111	3	85	670,125	123,000

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

To meet the primary objective of this research effort the following recommendations are made:

1. The nondestructive pavement evaluation procedure is theoretically sound. However, in its present form, it appears to give overly optimistic results and does not seem to be ready for general use. The main problem lies in the inability of determining the Young's moduli of subgrades where surface layers are concrete with thicknesses of about 10 inches or more and the variation between the failure criteria used in the destructive versus the nondestructive methodologies. Further investigation of Young's moduli can be accomplished by conducting nondestructive tests on pavements having similar subgrades but varying thickness of concrete surface layers. This should provide information regarding the dependency of the empirical modulus correction factor on the thickness of the concrete layer.

2. Nondestructive tests have been performed on several other Air Force Bases such as Shaw AFB, Blytheville AFB, Holloman AFB, and Mather AFB. Using these results and the information available from destructive test evaluations, comparison of pavement life such as those presented in this report should be made.

3. More research needs to be done to develop failure criteria for use in the nondestructive pavement evaluation.

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