AN EVALUATION PROCEDURE FOR RIGID AIRFIELD PAVEMENTS

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Background

History

The U.S. Air Force has enough airfield pavement to cover a 200-ft-wide section between Seattle and Miami. The Air Force Engineering and Services Center (AFESC) Pavement Evaluation Team (PET) must assess the structural integrity of these pavements. Traditionally, this has been done by destructive testing techniques requiring runway closures up to 72 hours. To reduce airfield closure time, AFESC has been investigating nondestructive testing (NDT) methods for airfield pavements since the early 1970's.

Early AFESC efforts in NDT focused on the wave propagation method. This method applied an impulse load to the pavement where the response was measured with accelerometers which were glued to the surface. The amplitude and phase shift of the waves from sensor to sensor were determined for various frequencies. Wave velocities were calculated for each frequency and were used to calculate wave velocities for each pavement layer. These wave velocities are proportional to the elastic properties of the pavement layer. Although sound in principle, the wave propagation technique has suffered primarily because it is slow (approximately 20 minutes per test) and the interpretation of data is difficult. These deficiencies led to AFESC's search for an alternate NDT device.

Concurrent with the development of AFESC's wave propagation method, another technique using impulse loading became prevalent in the highway industry. In this method, pavement response is measured in terms of surface deflections due to the impulse load. In 1985, AFESC contracted the New Mexico Engineering Research Institute (NMERI) to develop a prototype mobile self-contained NDT system that would use the surface deflection technology and overcome the disadvantages of the wave propagation system.

Several commercially available NDT systems were evaluated. The Dynatest Model 8000 Falling Weight Deflectometer (FWD) was selected as best suiting Air Force needs. The FWD rated high among the systems evaluated when considering such factors as reliability, accuracy, accessibility to test sites, speed of operation, and cost.

Based upon the success of several evaluations using the prototype system during early 1986, the Pavements Division of AFESC funded the U.S. Army Engineer Waterways Experiment Station (WES) to develop two production systems. Development of these systems included eliminating deficiencies found in the prototype. All three systems are currently in use--the prototype as a research tool and the production systems in the Air Force Airfield Pavement Evaluation Program.

Advantages

The Air Force FWD systems are equipped to perform complete airfield pavement evaluations on site. The system is air-transportable and can be used on any paved or semiprepared surface. The high mobility of the FWD allows an air base to maintain emergency access to the airfield while testing.

Manpower requirements have been reduced for field and laboratory testing. The FWD produces 15 times more data points per hour than does the wave propagation method and with better repeatability. The probability that "soft spots" will be identified before structural failure occurs is increased because the increased productivity provides better characterization of the variability of a pavement system. Subsequently, the reliability of the allowable load evaluation is increased.

An additional advantage of the FWD over techniques such as the wave propagation method is its ability to measure load transfer across jointed portland cement concrete (PCC) slabs. Joint load transfer efficiency has a significant effect on the the stresses developed at the bottom of a slab, therefore affecting the slab performance under aircraft load. The efficiency is expressed as the ratio of the unloaded deflection to the loaded deflection and is measured by placing the load plate on one side of the joint and the second sensor on the opposite side of the joint. The operator positions himself for these measurements with a closed-circuit television camera mounted on the FWD trailer and a monitor mounted in the cab.

Theory

Burmister introduced analytical techniques to estimate pavement response to load in layered

systems in the 1940's (1). However, these techniques have only recently been implemented (AASHTO Guide for Design of Pavement Structures) on a wide-scale basis. The primary impetus for the transition has been the computer hardware and software developments in the last 10 years.

Current mechanistic methods routinely being used are based upon multi-layered linear elastic theory. This theory assumes the materials in each pavement layer are loaded in their linear elastic range. The response of a pavement structure to loading can be calculated, given the elastic constants of the pavement layers. This is a major departure from the largely empirical methods of pavement design which are based primarily on historical performance data.

Development of Evaluation Procedure

Characteristics of the Testing System

The U.S. Air Force decided to change from the wave propagation technique of pavement evaluation in 1986. A deflection-based FWD was selected. The system applies a load of 26,000 lb through a 11.8-in.-diameter plate which approximates a single wheel load of many of the aircraft within the fleet. It can be air transported for evaluations around the world and can be easily transported cross country within the United States. The system applies a dynamic load that approximates the load pulse of a moving wheel.

Field Data Acquisition

With the FWD, large amounts of data can be collected rapidly. Therefore, data collection and analysis methods must be designed to handle these large data bases efficiently. With efficient systems, evaluation engineers can concentrate on quality of input and output rather than the mechanics of large data bases.

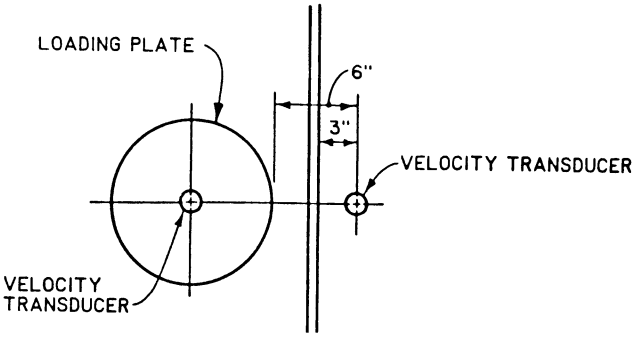
The testing scheme selected for airfield pavements includes conducting tests at 100-ft intervals alternating to either side of the center line of the feature. Tests are conducted near the wheel path of the predominate aircraft using the facility at the center of the PCC slabs or in the center of the largest piece of a shattered slab. Tests to evaluate load transfer are conducted on approximately 15 percent of the slabs tested. The position of the FWD loading apparatus and sensors is shown in Figure 1 for joint tests.

To ensure that the number of tests are adequate for approximating the true mean of the feature, a study was conducted on data collected on 148 PCC features and 68 composite features on 8 military airfields. Impulse stiffness modulus (ISM) was chosen as the control parameter for field evaluation. ISM is defined as:

$$ISM = \frac{\text{Force, lb}}{\text{Deflection at Plate Center, mils}}, \quad (1)$$

kips/in.

Figure 1. NDT equipment configuration for joint load transfer measurements.



A summary of the data base is shown in Table 1. The method for determining the number of tests requires that data be collected at the 100-ft intervals as outlined above. The coefficient of variation is then calculated for the feature. This value along with the number of tests for that feature would be compared to criteria to determine if the desired level of confidence had been achieved. Figure 2 shows the theoretical relationship between the coefficient of variation, number of tests, and confidence level for the assumption that the calculated mean value is within 10 percent of the true mean. It is desired that a point defining the coefficient of variation and number of tests for a given feature be above the line of the desired confidence level. For practical case, the theoretical lines may be too stringent. A practical upper limit for the number of tests was calculated as follows.

Table 1. Data base for determining number of tests.

	Average ISM, Kips/in.	Coefficient of Variation, %[a]
PCC Features		
No. of Cases - 148		
Maximum	8,813	77
Minumum	642	0.9
Average of all cases	3,691	16.4
Composite Features		
No. of Cases - 68		
Maximum	5,039	68
Minimum	509	3.2
Average of all cases	1,960	27.3

[a]Maximum and minimum coefficient of variation obtained on any of the features.

A confidence level, assuming a normal distribution, was calculated for each feature as given below:

$$Z = \frac{n(PE)^2}{(CV)^2} \quad (2)$$

where

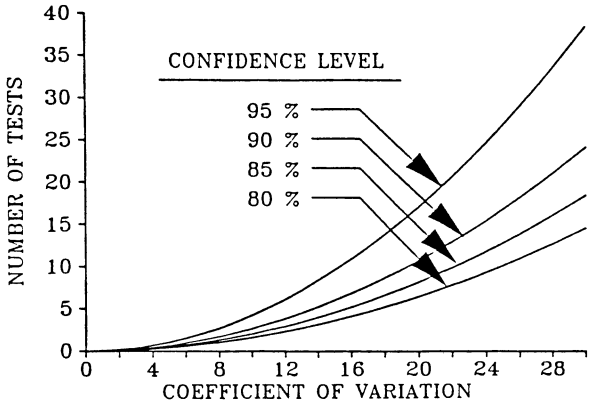
Z = the standard error multiplier for a given confidence level,

n = number of tests,

PE = allowable percent error in calculated mean, percent (10 percent was assumed for this case), and

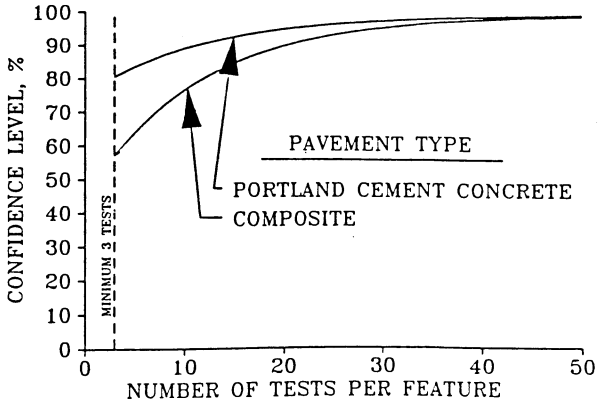
CV = coefficient of variation, percent.

Figure 2. Theoretical requirement for number of tests for sample mean to be within 10 percent of true mean.



A nonlinear regression line which is asymptotic at 100 percent confidence level was fitted to each pavement type, with results shown in Figure 3.

Figure 3. Confidence levels for data base pavements by pavement type.



Figures 4 and 5 apply the limits from Figure 3 to the theoretical curves in Figure 2. This procedure does not account for the size of the feature. Therefore, the same results would be obtained for a 50-ft-wide taxiway as for a 300-ft-wide runway.

Figure 4. Number of tests requirement for each feature on PCC pavements.

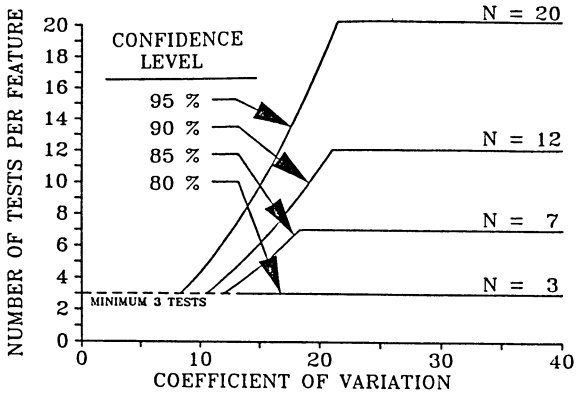
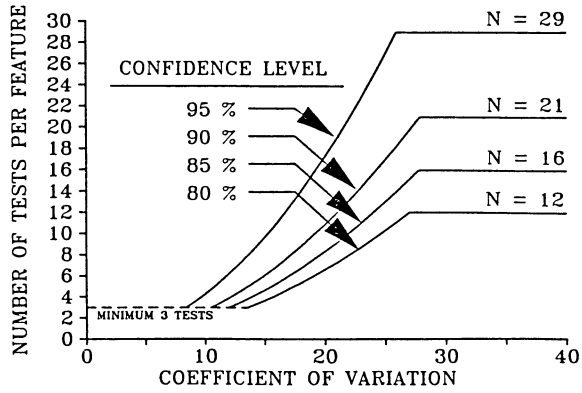


Figure 5. Number of tests requirement for each feature on composite (AC/PCC) pavements.



Analysis of Data

With some airfields having as many as 100 features and time limitations for output of final reports, methods for automatic data handling were developed. The first step is to select a representative deflection basin for each pavement feature. Simply taking the average of each deflection reading is not acceptable because high and low values may change the shape of the basin causing an inflection that cannot possibly exist in an elastic layer system. A computer program named BASIN (2) was developed to assist in selecting the data upon which the evaluation of each feature will be based.

The procedures incorporated in BASIN are as follows:

(1) Group data into areas of equivalent ISM. The program produces a plot on the screen and allows the operator to visually select areas to be grouped.

(2) Normalize the deflection to a common load.

(3) Determine average deflections for each offset distance.

(4) Compute area of each deflection basin.

(5) Compute logarithmic average of areas.

(6) Compute volumetric k for PCC and composite pavements

where

$$\text{Volumetric k, pci} = \frac{\text{Force (lb)}}{\sum_{N=1}^{7} \text{Area}_N * (\text{Dist. to Centroid}) * 2 * \pi} \quad (3)$$

(7) Compute an error function

$$\text{ERROR} = \left(\frac{\overline{ISM} - ISM}{\overline{ISM}}\right)^2 + \sum_{1}^{ND} \left(\frac{\overline{DF} - DF}{\overline{DF}}\right)^2 + \left(\frac{\overline{AREA} - AREA}{\overline{AREA}}\right)^2 \quad (4)$$

where

ISM = computed ISM,

DF = measured deflection,

AREA = computed area,

ND = number of deflection sensors,

$\overline{ISM}$ = average ISM,

$\overline{DF}$ = average deflection, and

$\overline{AREA}$ = average basin area.

(8) Select deflection basin with least error as representative basin for evaluating the feature or section.

The representative basin with pavement layer thicknesses are then input to a backcalculation program BISDEF (3). BISDEF uses an elastic layer program BISAR (4) to determine a set of modulus values that provide the best fit between the measured deflection basin and a computed basin when given an initial estimate of the modulus values, a range of modulus values, and a set of measured deflections.

For the evaluation of airfield pavements, a program AIRPAVE was developed to aid the engineer in calculating the allowable aircraft load and overlay requirements. AIRPAVE contains all the aircraft data on wheel configuration, pass to coverage ratios, minimum and maximum aircraft loads, and the limiting stress criteria (5) as given below and as shown in Figure 6:

$$\text{Allowable Stress}_{PCC} = \frac{R}{A + B \text{ LOG}_{10} (COV)} \quad (5)$$

or

$$\text{Design Factor} = \frac{R}{\text{Allowable Stress}_{PCC}} = A + B \text{ LOG}_{10} (COV) \quad (6)$$

where

$\text{Allowable Stress}_{PCC}$ = allowable tensile stress at the bottom of the slab, psi,

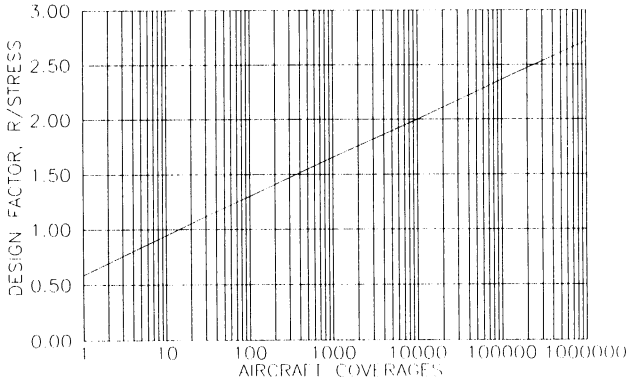
R = PCC flexural strength, psi,

A = 0.58901,

B = 0.35486, and

COV = Aircraft coverages.

Figure 6. Elastic layer limiting stress criteria for rigid airfield pavements (5).



For rigid pavements the thickness of the layers, the modulus values from BISDEF, the joint load transfer data, and the flexural strength of the PCC are input. From these data the allowable aircraft load is computed for either a single aircraft or for a group of aircraft as shown later in this paper.

AIRPAVE uses the deflection ratio from the joint efficiency tests, defined as:

$$\text{Load Reduction Factor} = \frac{\text{DEFLECTION OF UNLOADED SLAB}}{\text{DEFLECTION OF LOADED SLAB}} \quad (7)$$

The allowable load determined at the slab centers are reduced for poor joint transfer using load reduction factors. These factors are a function of the deflection ratio. The procedure was developed by using a finite element program to compute the maximum edge stress and deflection on either side of a joint for varying load transfer conditions. These results are shown in Figure 7. In developing the stress criteria, it was assumed that 75 percent of the maximum edge stress would occur (25 percent is carried by adjacent slab). The 75 percent stress corresponds to a deflection

ratio of 0.76. For deflection ratio less than 0.76, an adjustment factor can be computed to reduce the allowable load determined at the slab center to account for the load transfer capabilities at the joint (Figure 8). The load reduction factor falls between 0.75 and 1.00.

Figure 7. Relationship between deflection ratios and percent maximum edge stress.

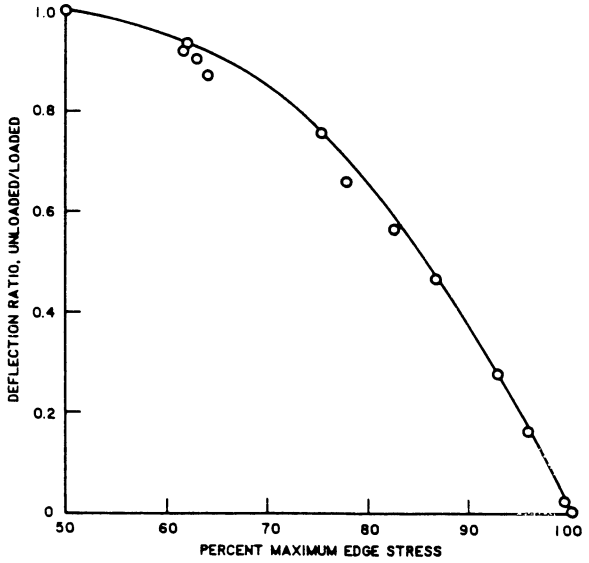
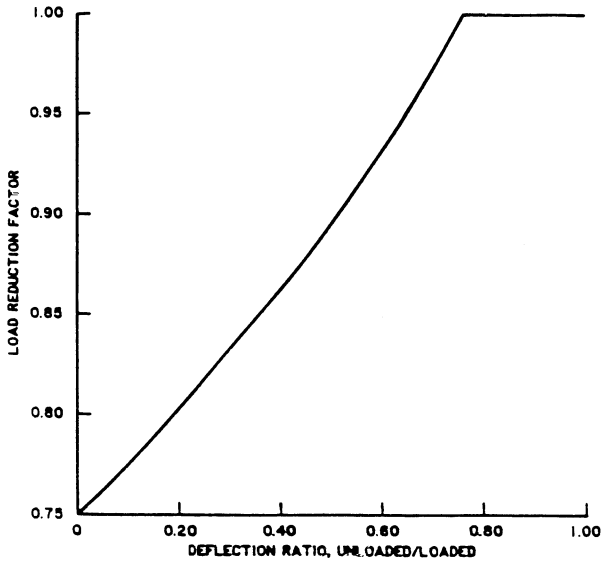


Figure 8. Load reduction factors for load transfer analysis.



The evaluation procedure presented above is being used extensively by the Air Force PET and has been selected by the Navy and Army for airfield evaluation. The Federal Aviation Administration is also evaluating this method for use on civil airports.

Application of Evaluation Procedure

Components of the Field Investigation

The field investigation portion of a nondestructive airfield pavement evaluation includes (1) FWD testing, (2) coring, (3) surface assessment, and (4) subsurface assessment. FWD testing simply involves executing the previously computed number of center slab and joint tests required for each feature. In parallel with the FWD operation, core samples are extracted from each feature for thickness confirmation and laboratory testing. Current PET practice involves extracting a minimum of three 6-in.-diameter cores from each rigid feature. More cores are taken from larger features, primarily to assess uniformity of construction. The surface assessment provides the team chief valuable information for appraising maintenance practices, threats to aircraft operations, and pavement performance. With respect to pavement performance, certain types of distresses indicate decline in structural integrity. The final component is subsurface assessment. This assessment will include a review of previous reports, construction drawings, geological information, and any other sources which might spread light on the type, thickness, and properties of materials underlying the airfield. Moreover, the assessment may include penetration testing and soil sampling through the core holes, particularly when subsurface information is not otherwise available. Each piece of the puzzle is necessary to get the "big picture" of how the pavement is performing and why.

A Case Study: Grissom AFB, Indiana

When discussing various approaches for presenting the Air Force evaluation procedure, the authors concluded a case study would be most helpful. Due to the variety of rigid pavement systems and an ample supply of recent data from a September 1987 evaluation (6), Grissom Air Force Base, Indiana, was chosen for the case study. Grissom AFB, located 15 miles north of Kokomo, is a Strategic Air Command base whose primary mission aircraft is the KC-135 tanker (a modified Boeing 707). Three pavement features (T10A, A07B, and A09B) were selected for study because they represented a variety in cross-section, traffic, and condition.

Table 2 summarizes the field investigation conducted for these three features. Cores were shipped from Grissom to AFESC at Tyndall AFB, Florida, for laboratory testing. PCC cores were tested for strength by tensile splitting in accordance with ASTM's standard test methods. Tensile splitting strength for each 6-in.-diameter core was converted to flexural strength using an empirical relationship (7). Subsurface layer thicknesses and classifications were known from a destructive evaluation conducted at Grissom in 1975 (8).

Following the field investigation and concurrent with the laboratory testing, FWD data analysis began. First, the ISM, which is the drop weight divided by the pavement deflection at the center of the load plate, is plotted for each test

within the feature (Figures 9-11). The graphs depict relative strength throughout the areas tested. Next, the previously discussed BASIN program is used to statistically select the representative deflection basin for each feature (Figures 9-11). Combining the thickness and material type information gathered during the field investigation with the representative basin, BISDEF can be run to determine resilient modulus (E_r) values for each layer. Information for the selected features derived from the field investigation, laboratory testing, and FWD data analysis is compiled in Table 3.

At this point, allowable gross load (AGL) computations may begin. As detailed earlier, the AIRPAVE computer code uses the resilient moduli, layer thicknesses, and Poisson's ratios based on material type (Table 3) in AGL computations. Table 4 presents the AGL's calculated for the case study with related explanatory data.

Table 2. Summary of field investigation.

Feature	No. of FWD Drops Center/Joint	Average Joint Efficiency, %	No. of Cores Taken	General Condition	Distress Types and Severity
A07B	9/2	95.5	3	Good	Medium-severity joint seal damage (throughout), popouts (throughout), low-severity corner spalls (throughout)
A09B	8/4	84.2	2	Fair	Low-severity durability cracking (occasional); high-severity joint seal damage (throughout); low-severity small and large patches (occasional); low- and medium-severity map cracking/crazing (occasional); low-severity joint spalling (occasional), low-, medium-, and high corner spalling (throughout); vegetation in cracks (occasional)
T01A	18/3	91.2	3	Very good	High-severity joint seal damage (throughout), popouts (throughout), low-severity corner and joint spalling (throughout)

Table 3. Summary of physical property data.

SUMMARY OF PHYSICAL PROPERTY DATA

FACILITY					OVERLAY PAVE			PAVEMENT			BASE			SUBBASE			SUBGRADE	
FEA.	IDENTIFICATION	LGTH (ft)	WDTH (ft)	GEN. COND.	THICK-NESS (in)	DESCRIPTION	$E \times 10^3$ FLEX	THICK-NESS (in)	DESCRIPTION	$E \times 10^3$ FLEX	THICK-NESS (in)	DESCRIPTION	$E \times 10^3$ K/CBR	THICK-NESS (in)	DESCRIPTION	$E \times 10^3$ CBR	DESCRIPTION	$E \times 10^3$ K/CBR
A07B	HANGAR ACCESS APRON	750	450	GOOD				15.00	PCC	6260	12.00	SILTY SAND (SM) W/GRAVEL	150				GRAY TO BROWN CLAY (CL)	13
										960			100					
A09B	RESERVE APRON	VAR	VAR	FAIR	3.00	PCC		8.00	PCC	6260	0.00						GRAY TO BROWN CLAY (CL)	13
										760								60
T01A	TAXIWAY S & SW END OF PARALLEL TAXIWAY	3700	VAR	VERY GOOD				17.00	RPCC	6260	12.00	SILTY SAND (SM) W/GRAVEL	150				GRAY TO BROWN CLAY (CL)	18
										950			100					

Table 4. AGL table with related explanatory data.

Feature	Pass Intensity Level	Pavement Capacity in kips for Aircraft Group Index Numbers 1	2	3	4	5	6	7	8	9	10	11	12	13
A07B	I	+	+	+	+	+	+	+	+	+	+	+	+	315
	II	+	+	+	+	+	+	+	+	+	+	+	+	361
	III	+	+	+	+	+	+	+	+	+	+	+	+	430
	IV	+	+	+	+	+	+	+	+	+	+	+	+	+
A09B	I	+	65	73	152	105	113	123	227	261	576	391	545	A
	II	+	+	53	167	+	124	134	249	283	627	446	623	A
	III	+	+	92	+	+	143	154	285	321	712	532	747	204
	IV	+	+	106	+	+	+	+	+	381	+	+	+	247
T01A	I	+	+	+	+	+	+	+	+	+	+	+	+	351
	II	+	+	+	+	+	+	+	+	+	+	+	+	401
	III	+	+	+	+	+	+	+	+	+	+	+	+	476
	IV	+	+	+	+	+	+	+	+	+	+	+	+	+

In reference to the allowable gross load table:

A Denotes lowest possible empty gross weight of any aircraft within the group exceeds the AGL of the pavement. Pavement cannot support aircraft for respective pass intensity level.

\+ Denotes no weight restrictions. AGL of the pavement exceeds the greatest possible gross weight of any aircraft in the group.

The load carrying capacities of the pavements reported herein are based on material properties representative of the in-place conditions at the time this field investigation was conducted.

Aircraft Group Index 1	2	3	4	5	6	7	8	9	10	11	12	13
C-123	A-7	F-111	C-130	C-7	737	727*	707	C-141	C-5	KC-10*	747	B-52
	A-10	FB-111*		C-9*	T-43*	KC-97	E-3*	B-1*		DC10	E-4*	
	A-37			DC9	C-119		C-135			L1011		
	F-4			C-54	EC-121		KC-135*					
	F-5			C-131			VC-137					
	F-15*			C-140								
	F-16			T-29								
	F-10X											
	T-33											
	T-37											
	T-38											
	T-39											
	T-46											
	OV-10											

*Controlling aircraft

		Allowable Gross Loading Limits for Aircraft Groups 1	2	3	4	5	6	7	8	9	10	11	12	13
British Units (kips)	A	35	5	50	60	20	40	85	105	135	325	230	300	175
	+	60	68	120	175	110	150	175	335	480	770	590	780	490
Metric (SI) Units (kilos x 1000)	A	16	2	23	27	9	18	39	48	61	147	104	136	79
	+	27	31	54	79	50	68	79	152	218	349	268	354	222

Level	Pass Intensity Level 1 2 3	4 5 6 7 8 9 10	11 12 13
I	300,000 passes	50,000 passes	15,000 passes
II	50,000 passes	15,000 passes	3,000 passes
III	15,000 passes	3,000 passes	500 passes
IV	3,000 passes	500 passes	100 passes
V	300,000 passes	50,000 passes	15,000 passes
VI	50,000 passes	15,000 passes	3,000 passes

A Denotes allowable gross loading less than basic weight of any aircraft having indicated gear configuration.

+ Denotes allowable gross loading greater than the maximum gross weight of any existing aircraft having indicated gear configuration.

Figure 9. FWD ISM's and representative basins selected for Feature T10A.

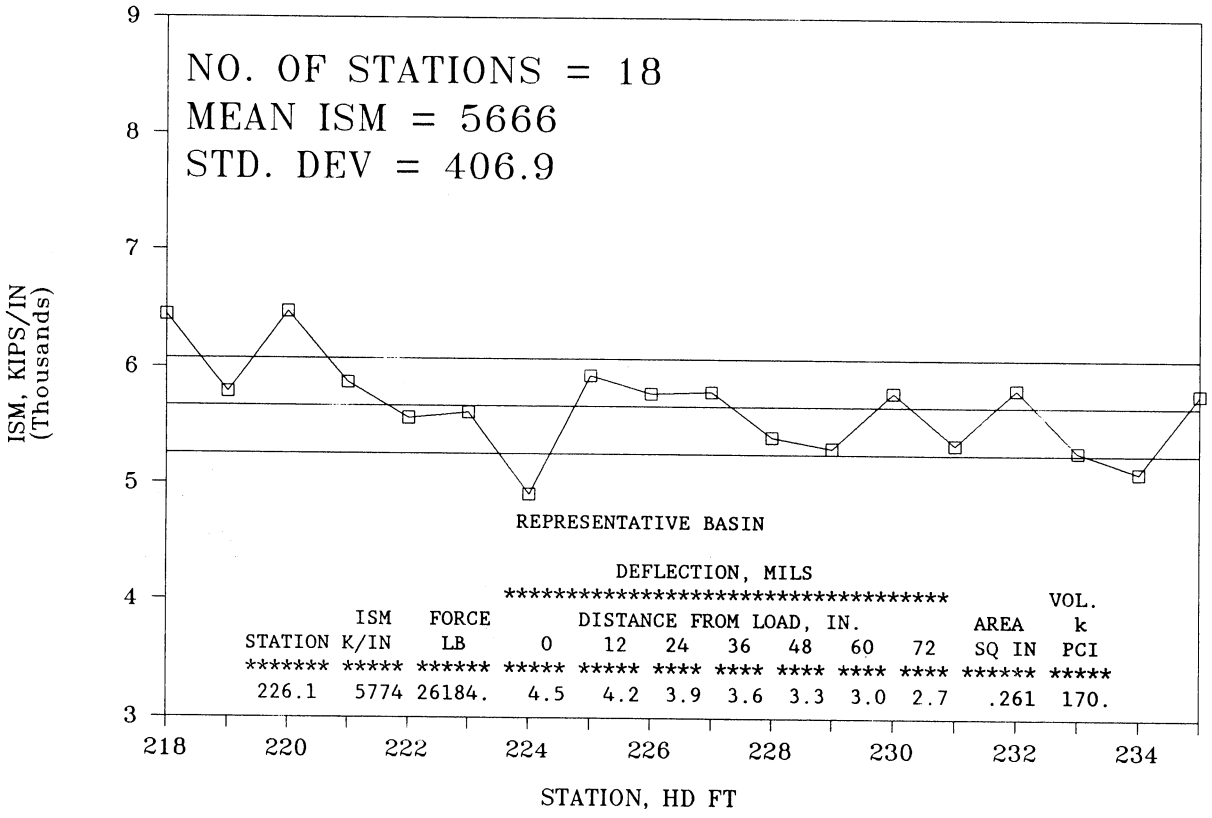


Figure 10. FWD ISM's and representative basins selected for Feature A09B.

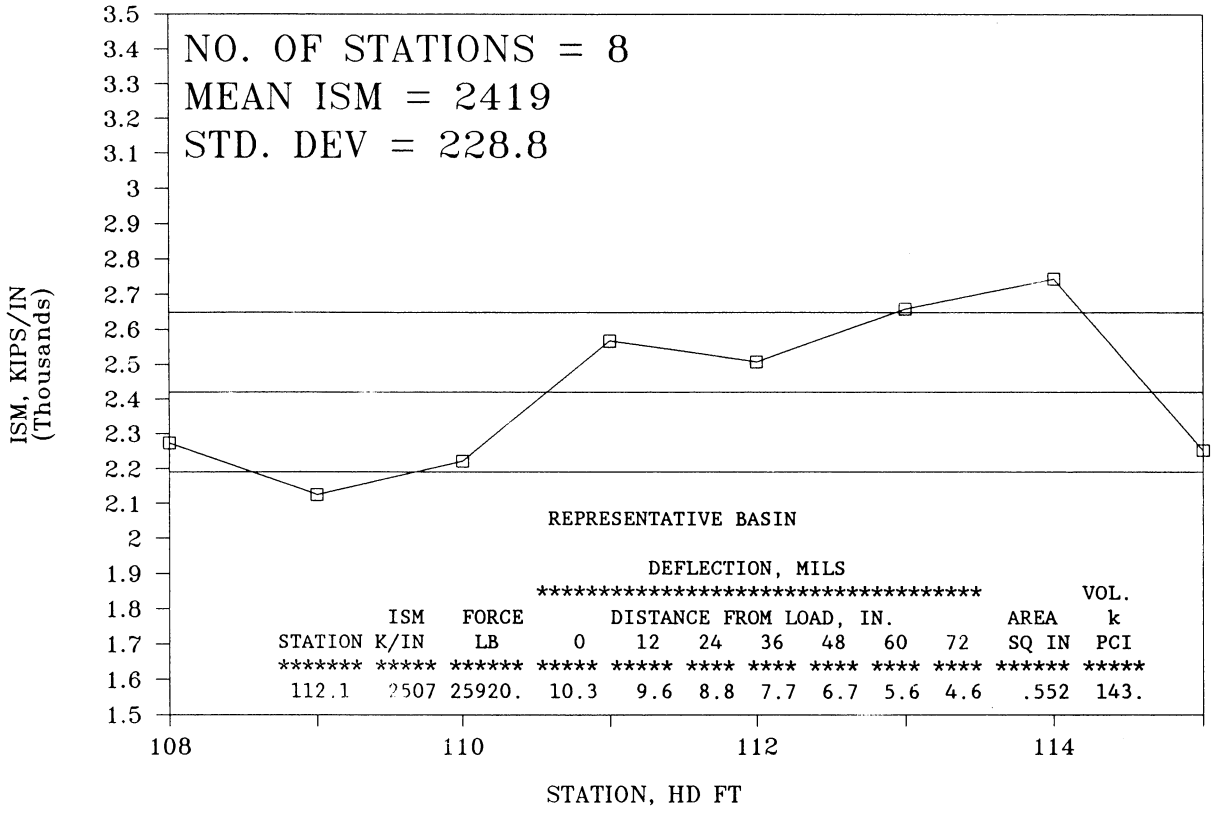
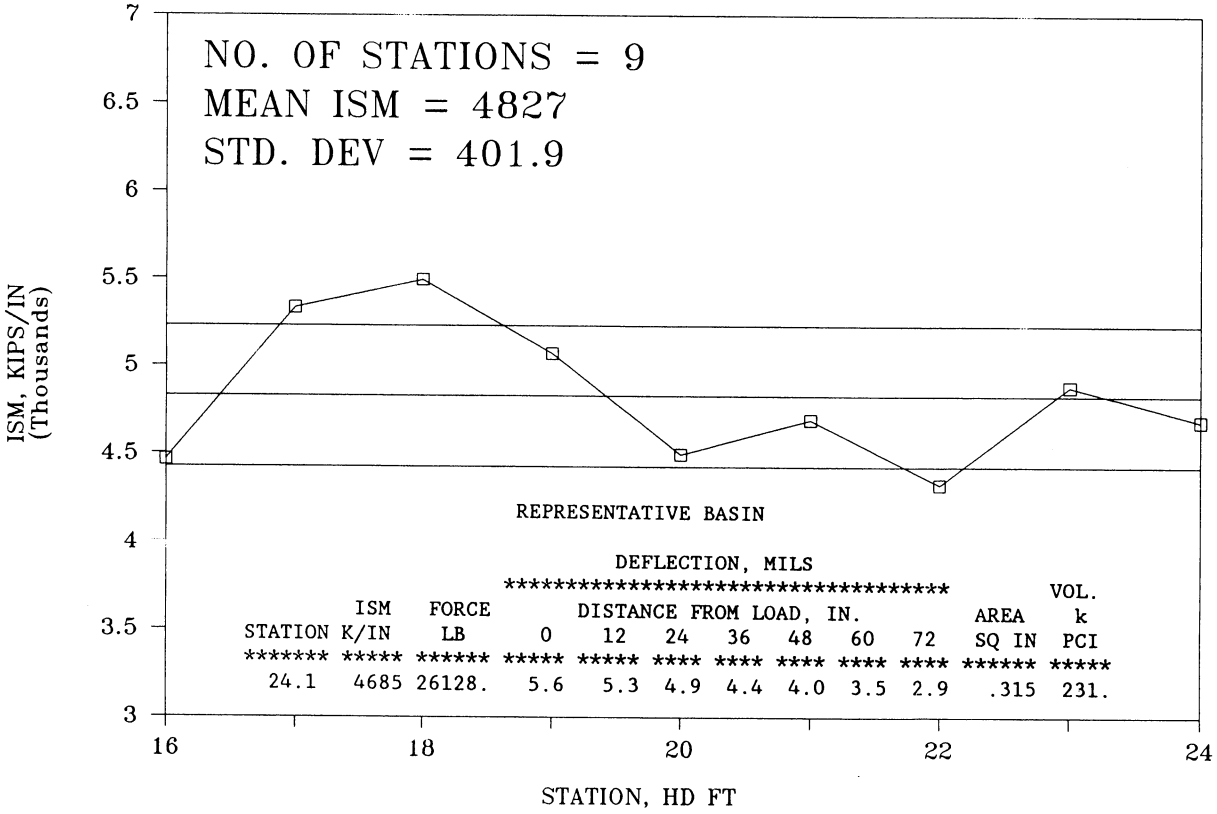


Figure 11. FWD ISM's and representative basins selected for Feature A07B.



Finally, this mass of information must be analyzed and distilled into concrete (pun intended) recommendations understandable to the clients, primarily the airfield manager and base pavements engineer. Hence, AFESC PET reports contain an example such as Figure 12 of how to use the AGL table and specific suggestions regarding load limitations and maintenance/repair needs (Table 5).

Conclusions

A method for rigid pavement evaluation was presented using the elastic layer theory with FWD data to assess the structural capacity of heavily loaded airfield pavements.

Methods were presented to (1) determine the number of tests required, (2) consider load transfer at joints, (3) reduce data to a manageable amount for analysis, (4) backcalculate layer moduli, and (5) determine allowable aircraft loads.

The Air Force is now committed to the elastic-layered method of pavement analysis. Rigid and flexible pavement design manuals based on this method are scheduled for publication, and an evaluation guide for determining pavement capacity with the FWD is currently being developed.

Acknowledgements

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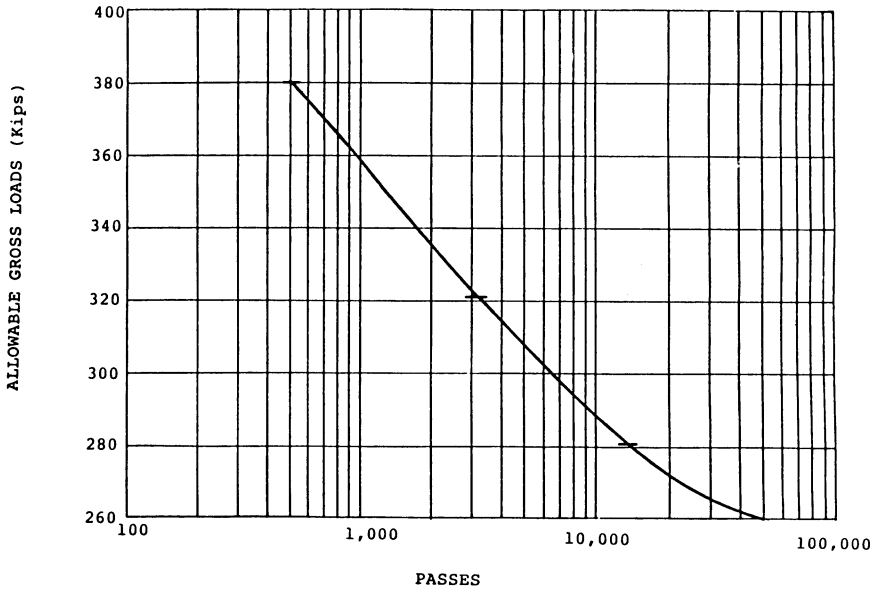
Figure 12. Example of how to use the AGL table.



Grissom AFB, Feature A09B, C-141 Aircraft, Group Index 9

Problem: Military Airlift Command wants to park a 360-kip C-141 on Feature A09B. How many passes can they expect to make before the pavement fails? (1 kip = 1,000 lb)

Solution: From Table 4, the allowable gross loads for a C-141 at pass intensity levels I-IV (50,000, 15,000, 3,000, and 500) are 261, 283, 321, 381, respectively. The weights and passes are plotted on semi-log paper. The completed graph indicates a 360-kip C-141 can make approximately 1,000 passes on Feature A09B before the pavement fails.

Table 5. Evaluation summary.

Feature	Load Limitations	Maintenance/Repair Recommendations
A07B	Feature can support most aircraft at maximum load for prescribed pass levels. B-52 is the one exception--adhere to weight limits listed for corresponding pass levels.	Replace joint sealant within 2 years. Instigate corner spall repair to prevent FOD and retard further slab deterioration.
A09B	Adhere to weight limits listed for corresponding pass levels. Most significant limitations are for aircraft in Groups 3, 9, and 13.	Clean and reseal joints immediately. Instigate immediate corner and joint spall repair to eliminate existing FOD hazard and retard further slab deterioration. Clean and seal cracks. Monitor progression of scaling--surface treatment may be necessary in the future.
T10A	Feature can support most aircraft at maximum load for prescribed pass levels. B-52 is the one exception--adhere to weight limits listed for corresponding pass levels.	Clean and reseal joints immediately. Instigate corner and joint spall repair to prevent FOD and retard further slab deterioration.

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