Nondestructive Evaluation Equipment for Airfield Pavements

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Nondestructive testing (NDT) has provided a rapid means of assessing the structural capacity of airfield pavements during periods of increasing traffic and loadings. A wide range of test equipment is available for airport owners to select from. Various commercially available NDT equipments were applied to the structural evaluation of airfield pavements using a layered elastic method of analysis. Seven different NDT devices were evaluated. Three of the devices imparted vibratory loads to the pavement, whereas four devices applied impulse or falling-weight loads. NDT data were collected on 12 pavements that included thick and thin flexible, rigid, and composite structures over fine- and coarse-grain subgrades. Backcalculated subgrade moduli from the devices were compared. These data were used for estimating the allowable load and overlay requirements for a selected aircraft to demonstrate the variability that could be obtained using different devices.

During the past 10 to 15 years, much effort has been devoted to the development of nondestructive structural evaluation of pavements; as a result, several test devices and analytical procedures have been developed. The work has been sponsored by such federal agencies as the Navy, Army, Air Force, FAA, and FHWA, as well as many state departments of transportation, port authorities, and others. Research has been conducted by federal and state agencies, universities, private research organizations, and consultant engineers. Many reports have been published describing the development and application of the methods.

In October 1982, the U.S. Air Force Engineering and Services Center (AFESC) sponsored a study that was conducted by the U.S. Army Engineer Waterways Experiment Station (WES) to compare the results from several nondestructive testing (NDT) methods on selected Air Force airfield pavements (*1*). The purpose of the study was to provide AFESC with an assessment of the nondestructive approach to pavement evaluation so that the Air Force could make sound decisions as to the possible uses and benefits of NDT pavement evaluation schemes.

The scope of the project involved comparisons of selected NDT equipment and procedures on representative airfield pavements and a comparison of the NDT results to those obtained from the standard Air Force evaluation procedures based on test pit measurements. WES selected six leading firms with demonstrated NDT capabilities. These firms represented the state of the art in terms of commercial NDT equipment and available analytical evaluation methods. In addition, WES demonstrated three NDT schemes that it had developed, and AFESC demonstrated its NDT evaluation method. The field demonstrations were conducted within five selected test areas at MacDill Air Force Base (AFB), Tampa, Florida, during October and November 1982.

From the MacDill study, it was recommended that the comparison should be repeated at other sites to produce more conclusive results (*1*). These sites should cover more typical pavements over fine-grained soils (clays and silts), test pit data should be collected concurrently with the NDT data, and the pavements should be of such design that a range of allowable loads and overlay thicknesses would be anticipated so that a better comparison of results could be made. A set of test areas that require rehabilitation under common aircraft loads was also identified as a requirement. A standard evaluation procedure was also recommended.

The Navy, Air Force, Army, and FAA are in various stages of implementing a layered elastic design and evaluation procedure for airfield pavements. NDT offers a useful method for determining the modulus values for input into the design and evaluation. In order to specify the equipment requirements and also compare the results to conventional design and evaluation procedures, a field verification is required.

PURPOSE AND SCOPE

A layered elastic method of analysis was used to examine applicability of various NDT equipment to the structural evaluation of airfield pavements. All existing available NDT equipment (representative types) used for airfield testing were covered and predicted moduli from the various devices were compared.

NDT EQUIPMENT EVALUATED

Seven different NDT devices were evaluated. Three of the devices impart vibratory loads to the pavement, whereas four devices are impulse or falling-weight loading devices. The devices and specific characteristics of each are given in Table 1. Detailed descriptions of each device are given in the following paragraphs.

Kuab Model 50 Falling Weight Deflectometer (FWD)

The Kuab FWD is a trailer-mounted impulse loading device that produces its load using a unique two-mass system in which a falling weight is dropped onto a buffered second weight to

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TABLE 1 NONDESTRUCTIVE TESTING DEVICE CHARACTERISTICS

Device Name	Dynamic Force Range, lbf	Load Transmitted by	Number and Type of Deflection Sensors	Deflection Sensor Spacing
Kuab FWD	3,000 to 15,100	Sectionalized circular plate 11.8 in. dia.	7 Seismometers	Fixed at 0, 8, 12, 18, 24, 36, 48 in.
Dynatest HWD	10,000 to 55,000	Circular plate 11.8 in. or	7 Geophones	Variable 12 to 96 in.
Dynaflect	1,000 peak to peak	Two 16 in. dia. x 2 in. width urethane-coated steel wheels	5 Geophones	Variable 0 to 48 in.
Dynatest FWD	1,500 to 27,000	Circular plate 11.8 in. or 17.7 in. dia.	7 Geophones	Variable 12 to 96 in.
Road Rater 2008	500 to 7,000 peak to peak	Circular plate 18 in. dia.	4 Geophones	Variable 24 to 48 in.
WES 16-Kip	500 to 30,000 peak to peak	Circular plate 18 in. dia.	4 Geophones	Variable 24 to 60 in.
Phonix FWD	2,300 to 23,000	Circular plate 11.8 in. dia.	6 Geophones	Variable 8.3 to 58 in.

produce pavement deflections. The load is transmitted to the pavement by an 11.8-in.-diameter plate that is segmented into quarters and cushioned with a corrugated rubber pad. The model tested has an impulse range of 2,600 to 14,000 lb. The testing system is powered by batteries on the trailer that are charged by a separate alternator on the towing vehicle. Deflections are measured by seven seismometers at fixed locations at and away from the loading plate. The Kuab FWD that was tested was able to perform loadings at distances up to 28 in. below the pavement surface and was equipped with a coring rig, but neither of these features was used or evaluated.

Pavement loadings can be produced at four adjustable drop levels. There is no limitation to the sequence or number of drops that can be run at a given location. Load and deflection data are produced with each drop and recorded with an MS DOS computer. The computer produces a paper copy as the data are collected and can also store the information to magnetic tape.

Dynatest Model 8081 Heavy Weight Deflectometer (HWD)

The Dynatest 8081 HWD is a trailer-mounted device capable of producing impulse loads from 8,000 to 55,000 lb. The single-pulse transient load is generated by a weight dropping on rubber pads that transmit the force to the pavement through either an 11.8- or 17.7-in.-diameter steel plate cushioned with a thin rubber pad. The testing system is powered by batteries on the trailer that are charged by a heavy-duty alternator on the towing vehicle. Deflections are recorded by seven geophones that are placed 1 ft apart starting at the center of the load plate, but the outer six can be varied from 12 to 96 in. away from the plate.

The falling weight system is controlled by an MS DOS computer and can produce up to five loadings selected from any combination of four adjustable drop heights. Load and deflection data are recorded on paper with each loading and can be automatically saved to a magnetic disk.

Dynaflect

The Dynaflect is a trailer-mounted electromechanical system for measuring the dynamic deflection of a pavement. Pavement deflection is produced by the counterrotation of two eccentrically loaded masses rotating at a fixed frequency of 8 Hz. A 1,000-lb, peak-to-peak sinusoidal load is transmitted to the pavement by two 4-in.-wide, 16-in. outside diameter polyurethane-coated steel wheels spaced 20 in. apart.

Once the mass rotation has been initiated and the loading wheels lowered, the Dynaflect produces constant pavement deflection and can be towed along the pavement in this manner. Pavement deflections at a test point are measured with five geophones that are aligned between the two wheels and lowered when deflection measurements are desired. One geophone is placed directly between the wheels, and the others are spaced at 1-ft intervals away from the loading wheels. Deflections readings are displayed on visual readouts by the electronic control system and can be produced on paper by the companion printer.

Dynatest Model 8003 FWD

The Dynatest Model 8003 FWD is a trailer-mounted, impact load device that can produce a load between 1,500 and 25,000 lb. The single-pulse transient load is generated by a weight dropping on rubber pads that transmit the force to the pavement through a 11.8-in.-diameter steel or dense rubber plate cushioned with a thin rubber pad. The testing system is powered by batteries on the trailer that are charged by a heavy-duty alternator on the towing vehicle. Deflections are recorded by seven geophones that are typically placed 1 ft apart from the center of the load, but the outer six can be varied from 12 to 96 in. away from the plate.

The falling weight system is controlled by a Hewlett-Packard IPC and can produce up to five loadings selected from any combination of four adjustable drop heights. Load and deflection data are recorded on paper with each loading and can be automatically saved to a magnetic disk.

Road Rater Model 2008

The Road Rater Model 2008 is an electrohydraulic vibratory loading system with an 8,000-lb reaction mass. The system is trailer mounted and has a self-contained power supply that supports the electronic and hydraulic systems. The vibratory load can be adjusted up to 7,000 lb peak-to-peak over a frequency range from 5 to 100 Hz and operates at a standard frequency of 20 Hz. The load is transmitted to the pavement through an 18-in.-diameter steel plate and is monitored by three load cells mounted on the plate.

Four geophones are used to measure deflection, with one measuring at the center of the plate and three at locations away from the plate. The deflection, load, and frequency data are recorded on a digital printer contained in the system controller box.

WES 16-kip Vibrator

The WES 16-kip vibrator is an electrohydraulic vibratory loading system with a 16,000-lb reaction mass. The system is contained in a 36-ft semitrailer along with supporting power supplies and automatic data recording equipment. The vibratory load can be varied up to 30,000 lb peak-to-peak over a frequency range of 5 to 100 Hz. The standard test frequency is 15 Hz, and the load is transmitted to the pavement through an 18-in.-diameter steel plate and measured by three load cells mounted on the plate. Up to five velocity transducers located at the plate and at points away from the plate are calibrated to measure deflections.

The load and deflection results are recorded on an $x-y$ plotter and a digital printer. The $x-y$ plotter records load versus the deflection of the velocity transducer on the plate as the vibratory load is increased from zero to maximum. The plot is used to calculate the dynamic stiffness modulus (DSM), which is the slope (load/deflection) of the plot between loads of 10 and 14 kips. Deflection results of all the sensors can be printed at any time as the load is swept from zero to the maximum of 30,000 lb.

Phonix ML10000 FWD

The Phonix FWD is a trailer-mounted device that can impart a dynamic impulse load of between 2,300 and 23,000 lb to the pavement surface. The load is produced by mechanically raising a circular mass to one of five set drop heights and then dropping it onto rubber pads that transmit the force to a padded 11.8-in.-diameter steel plate. The entire testing system operates from two 12-volt batteries that are contained in the trailer, and which in turn are charged by a small generator. Deflections are recorded by six geophones, five of which can be adjusted to any position from 8.3 to 58 in. from the loading plate.

Data produced by the Phonix FWD are recorded by an MS DOS system computer. The Phonix FWD is set up to produce three drops from the chosen height. The deflection of each sensor is recorded from each drop height; the load is recorded only on the third drop. The load and deflection data from the third drop are automatically recorded on magnetic media by the computer.

EXPERIMENTAL DESIGN AND DESCRIPTION OF TESTS

Two different phases of tests were performed in this study (*2*). First, calibration and repeatability experiments were performed to analyze the ability of each device to perform NDT consistently and reliably. All of these experiments were conducted over a 3-day period at WES. Then tests were performed at five different airfields for the collection of NDT and in situ pavement strength data. The NDT data were collected in a 2-week period immediately following the conclusion of the experiments performed at WES, whereas the in situ pavement strength tests were performed at each site following the completion of the NDT field tests.

Short-Term Repeatability

The experiment used to analyze the short-term repeatability of each machine involved having each device perform 25 tests at one test location in as short a period of time as the device would allow. The tests were performed at maximum load except for the Dynatest HWD, which would have overranged its deflection sensors in this experiment at maximum load, and each device performed this experiment on an asphalt concrete (AC) and a portland cement concrete (PCC) pavement. The vibratory devices and the Kuab FWD all performed the tests in one test sequence without lifting the loading plate. The Dynatest FWD and Dynatest HWD performed the tests in five series of five drops each. The Phonix FWD performed the tests in 25 series of three drops each with the recorded test data being the last drop of each series.

Field Testing

The field testing was performed on an array of airfield pavements. The pavement array is designed to include the three

TABLE 2 AIRFIELD AND PAVEMENT TYPES BY SITE

Site	Airport	Pavement Description
1	Brookley Airport Mobile, AL	17-in. PCC
2	Brookley Airport Mobile, AL	2-in. AC/10-in. PCC
3	NAS Pensacola, FL	10-in. PCC
4	NAS Pensacola, FL	2.5-in. AC
5	Robins AFB Warner-Robins, GA	8-in. AC
6	Robins AFB Warner-Robins, GA	8-in. AC/7-in. PCC
7	Birmingham ANG Birmingham Municipal, AL	7-in. PCC
8	Birmingham ANG Birmingham Municipal, AL	7-in. AC/7-in. PCC
9	Birmingham Army Guard Birmingham Municipal, AL	5-in. AC
10	Birmingham Municipal, AL	2-in. AC/7-in. PCC
11	Sheppard AFB Wichita Falls, TX	21-in. PCC
12	Sheppard AFB Wichita Falls, TX	6-in. AC

types of pavement surfaces—rigid, flexible, and composite; two relative strengths of pavements—thick and thin; and two types of subgrade—fine- and coarse-grained. Combining each pavement type, strength, and subgrade type yielded an array of 12 test sites. Five airfields were selected for the performance of this phase of testing. The airfields and the pavement types are presented by site in Table 2 and are shown in the pavement array in Figure 1.

NDT was performed to determine the effects of pavement type, thickness, and subgrade type on the deflections from each machine. In order to compare deflections between machines, the force outputs of each device were selected to maximize the number of devices operating at the same load level. These selected force outputs were called target loads, and each device operated at its maximum load level. The direct sampling tests will help characterize the in situ conditions of each site for comparison with the backcalculation data. The NDT and direct pavement sampling that are described were performed at each test site.

Nondestructive Testing: Replicate Tests

The purpose of these tests was to study the effects of the three variables in the pavement array on all the machines as well as to study the effect of load variation within the abilities of each device over the pavement array. In order to ensure that these effects could be identified, as many external noise variables as possible were blocked out of the experiment. To block out the variation due to change in thickness or material properties from one point to another, tests were performed on one point at each pavement site. This test point was designated the reference point at each test site. The effects of temperature were blocked out by performing the replicate tests either in the early morning or in midafternoon when the temperature would be fairly constant. The loading applied by the devices was also blocked. All loads 15,000 lb and less were conducted in Block 1 tests, whereas the loads heavier than 15,000 lb were conducted in Block 2 tests. Block 1 tests were conducted first at each pavement site to eliminate any effects that may have been caused by consolidation of the pavement layers under the heavier loads. There are 19 device and load combinations in Block 1 and 4 in Block 2. The devices and their respective target loads in each block are presented in Table 3.

All of the Block 1 and 2 tests were replicated three times at each pavement site. The order of testing for each replicate was randomized. Each replicate test consisted of bringing a device over the reference point and conducting three tests at the specified load. Therefore, for a given device and load,

NDT EQUIPMENT EVALUATION

EXPERIMENTAL DESIGN

SUBGRADE	FINE		COARSE	
STRENGTH	THICK	THIN	THICK	THIN
TYPE				
AC	Site #12 Sheppard AFB 7" AC 20" Base 14 CBR Subgrade	Site #9 Birmingham 4" AC 4" Base 28" Subbase 16 CBR Subgrade	Site #5 Robins AFB 8" AC 8" Base 46 CBR Subgrade	Site #4 Pensacola NAS 5.5" AC 13.5" Base 16 CBR Subgrade
PCC	Site #11 Sheppard AFB 21" PCC 6" Base k = 81 pci	Site #7 Birmingham 7" PCC k = 82 pci	Site #1 Mobile Brookley Field 18" PCC k = 294 pci	Site #3 Pensacola NAS 10" PCC 4" Base k = 303 pci
COMPOSITE	Site #8 Birmingham 6.5" AC 7" PCC k = 27 pci	Site #10 Birmingham 2" AC 7" PCC 14" Base k = 192 pci	Site #6 Robins AFB 10" AC 7.5" PCC k = 476 pci	Site #2 Mobile Brookley Field 2" AC 10" PCC

FIGURE 1 Pavement array of field testing sites.

TABLE 3 TARGET LOAD LEVELS FOR REPLICATE TESTING

	Target Load, kips							
	Block 1					Block 2		
Device	1	5	7	10	15	20	25	50
Kuab FWD		X	X	X	X			
Dynatest HWD				X	X		X	X
Dynaflect	X							
Dynatest FWD				X	X		X	
Road Rater	X	X	X					
WES 16-kip	X	X	X	X	X			
Phonix FWD				X	X	X		

there were nine deflection basins collected. The 19 load and device combinations in Block 1 yielded 171 deflection basins at each site. Thirty-six deflection basins were collected for each site in Block 2 testing.

Direct Pavement Sampling

The tests in the direct pavement sampling investigation were performed in a test pit that was approximately 4 by 4 ft and located directly beneath the NDT reference point at each site. In-place testing was performed on each layer, and then an undisturbed sample was extracted from the subgrade at each test location. Bag samples were also collected from the granular base and subbase layers and from the subgrade materials for laboratory testing.

The in-place testing at the flexible pavement test sites consisted of determining the California bearing ratio (CBR), water content, and density of each pavement layer. For the PCC and composite pavement test sites, plate-bearing tests were conducted directly beneath the PCC slab. Density and water content were determined on each layer.

TEST RESULTS AND DATA ANALYSIS

Short-Term Repeatability

The analysis of the data for each device and both pavement types included determining coefficient of variation (COV) of each deflection sensor over all 25 tests, determining the variation in deflection and load over the 25 tests, and making notations on any significant changes or anomalies in the test data.

The deflections of the first sensor for each test from each of the devices on the AC and PCC pavements are shown in Figure 2. Note that the deflection data for the Dynaflect were multiplied by 15 for ease of illustration. Each first drop of the five-drop series for the Dynatest FWD on PCC showed consistently lower deflection than the other four drops. The deflection difference in the averages of the five first-drop readings and the other 20 readings was 11.2 percent. The 20 consistent readings had a COV of 0.36 percent. The Dynatest HWD exhibited this same phenomenon on the AC pavement on three of the five series of drops. Those three deflections varied 10.4 percent from the other 22 deflections, which had a COV of 0.89 percent. The seating load for both of these devices may not be high enough to settle the plate onto the pavement surface. However, this phenomenon was not exhibited on the other corresponding pavement surface by either of the Dynatest devices.

As the Dynatest FWD tests on AC in this experiment progressed, the deflections increased; and in particular, the second drop of each five-drop series showed consistently higher deflection, and the second drop of the last series of five tests overranged the sensor, which is rated up to 80 mils. A plot of the next four sensors away from the plate of the Dynatest FWD does not show this higher deflection on the second drop of the series but, in fact, shows slightly higher deflection on the first drop of the series. Note that except for the last series, when the deflection sensor was overranged, none of these deflection readings varied by more than 3 percent from the other readings. This variation is considered within the sensitivity of the sensors.

The Kuab FWD exhibited a higher deflection and corresponding lower stiffness value on the first drop of its 25-drop sequence on the asphalt surface. This is the same phenomenon exhibited by the Dynatest devices, noting that the Kuab FWD did not raise the plate during its operation for this test. The Phonix FWD displayed a higher load for its first recorded test; however, this is not a function of the seating load. Recall that the Phonix FWD only records the load on the third drop of its required three-drop test and then raises the plate before another test is performed.

The scale of Figure 2 flattens out the data, but the Road Rater had three distinct measuring periods in its deflection data on the asphalt pavement. During each of these measuring periods, the deflection of the sensor at the plate would consistently decrease to between 12 and 20 percent below the initial deflection in the period, then increase to the approximate level found at the beginning of the period, and then drop to about the same level. The shift was not evident in the loading from the Road Rater; the COV of load throughout the test was only 0.8 percent. The shift was also noticed in the other sensors, but the trend was less apparent as the distance from the load increased. A consistent, constant drop over the data might be expected with a vibratory device on AC pavement (as was evident with the WES 16-kip), but the large drops noticed in the data are suspect.

The COV of deflection for each of the device sensors on each of the pavement types is shown in Figure 3. Except for the Road Rater on the asphalt pavement, all of the devices showed an increase in COV of deflection as the sensor's distance from the plate increased, as expected. The Road Rater on the AC section showed a dramatic increase in COV of deflection of the sensors close to and at the loading plate. The Road Rater also showed the highest COV of deflection on the PCC pavement. The COV of deflection for the Road Rater on the PCC ranged from 3.2 to 7.4 percent depending on the sensor, whereas the other devices ranged from only 0.3 to 2.6 percent. The high COV for the last sensor of the Phonix FWD on the AC was due to a bad reading on one test.

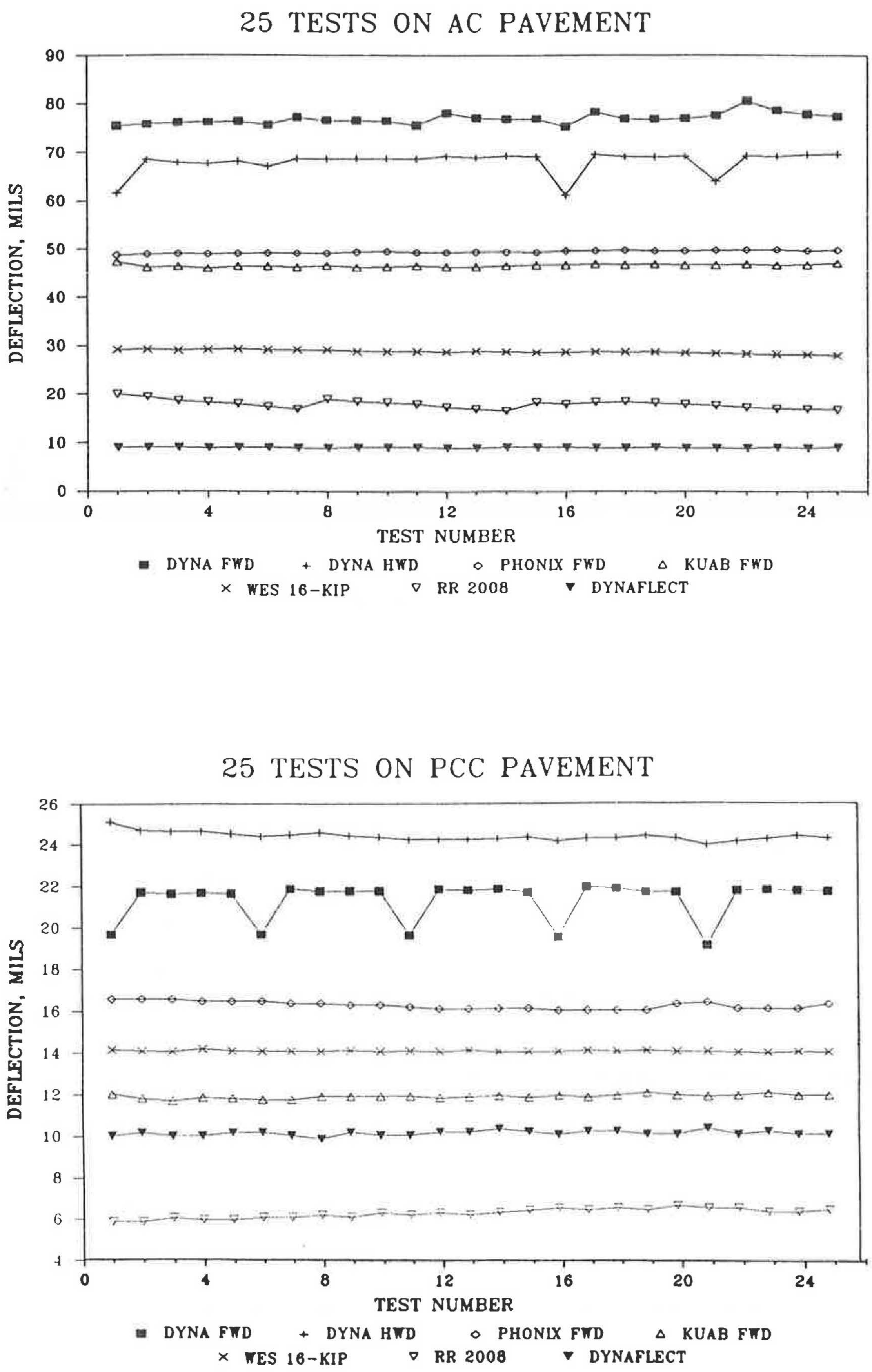
Field Testing: Deflection Test Results

Deflections for each device at each of the 12 sites are presented in Table 4. These data are the average of the last two tests of three that were conducted during the three replicate tests. Therefore, these data are the average of six randomly collected deflection basins at the same location.

Direct Pavement Sampling

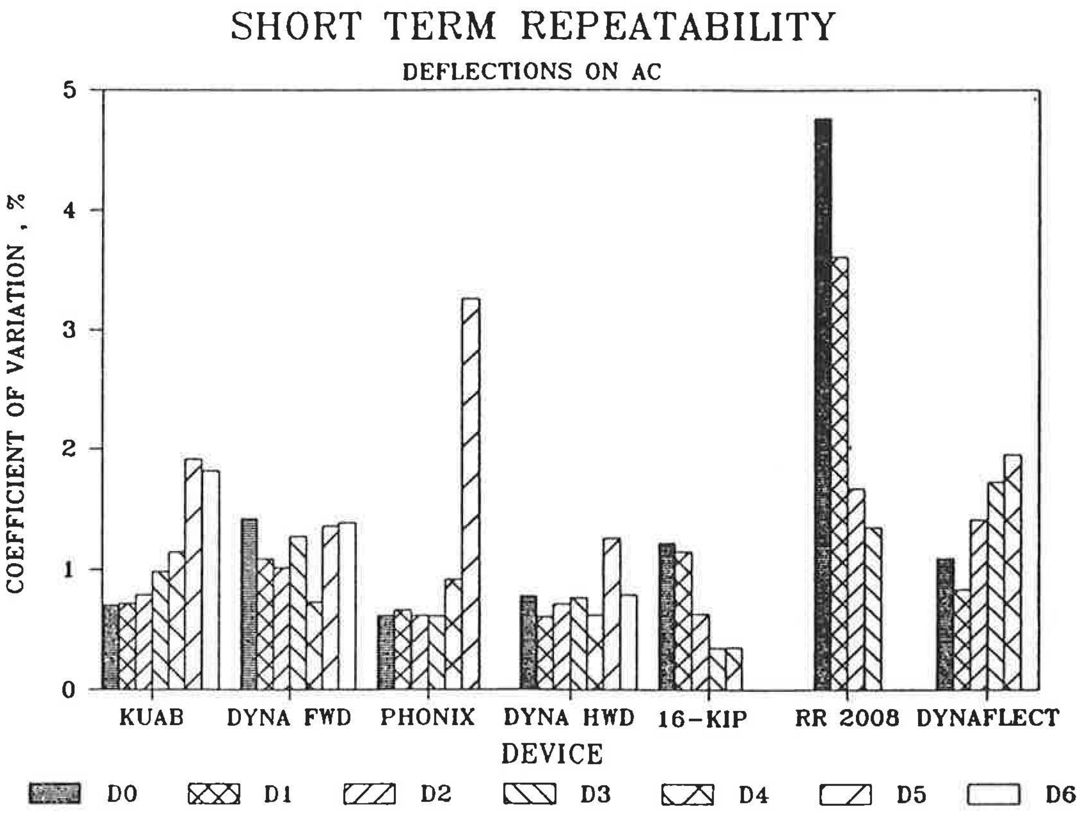
California Bearing Ratio Tests

CBR tests were conducted beneath the asphalt surface pavements in accordance with MIL-STD-621A (*3*), Method 101. CBR is a measure of the soil resistance to penetration of a


25 TESTS ON AC PAVEMENT

25 TESTS ON PCC PAVEMENT

FIGURE 2 First sensor deflections from short-term repeatability experiment.



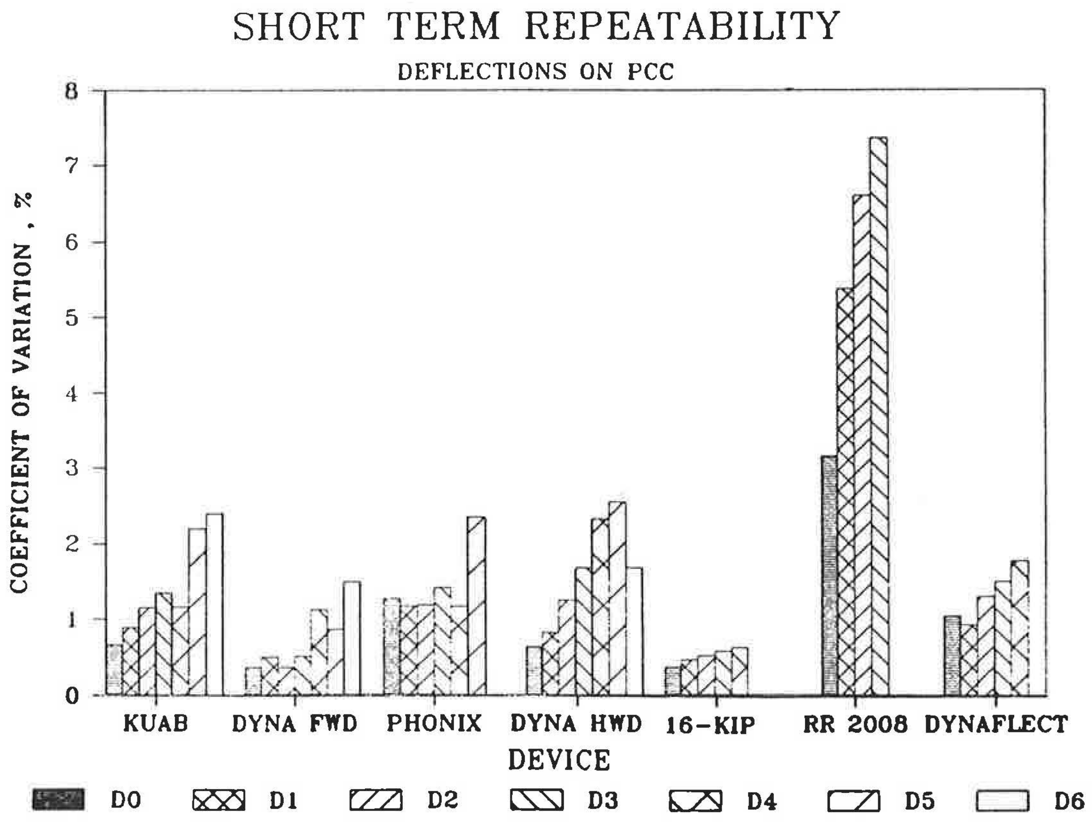


FIGURE 3 Coefficient of variation of deflections from short-term repeatability experiment.

TABLE 4 MEAN DEFLECTION BASINS

KUAB DEFLECTIONS, MILS

SITE	MEAN FORCE LBS	D0 MEAN	D1 MEAN	D2 MEAN	D3 MEAN	D4 MEAN	D5 MEAN	D6 MEAN
1	14116	2.67	2.55	2.43	2.50	2.40	2.23	2.11
2	14160	5.36	4.11	4.02	3.77	3.51	2.97	2.72
3	14151	3.70	3.54	3.40	3.16	3.03	2.62	2.20
4	14105	22.25	16.43	12.68	8.73	6.27	3.67	2.52
5	13928	11.73	8.45	6.44	4.40	3.05	1.49	0.88
6	14100	11.83	6.89	5.32	4.71	4.35	3.59	2.82
7	14241	10.15	9.72	9.41	8.69	7.99	6.29	4.67
8	14160	9.28	7.21	6.25	5.04	4.04	2.75	1.74
9	14126	24.98	13.83	7.99	3.45	1.80	1.48	1.42
10	14070	6.75	6.10	5.86	5.35	4.81	3.76	2.72
11	14403	2.15	2.01	1.88	1.82	1.80	1.71	1.62
12	14431	31.77	24.10	19.38	13.20	9.29	4.77	3.30

DYNA HWD DEFLECTIONS, MILS

SITE	MEAN FORCE LBS	D0 MEAN	D1 MEAN	D2 MEAN	D3 MEAN	D4 MEAN	D5 MEAN	D6 MEAN
1	50707	8.23	7.80	7.40	6.92	6.40	5.95	5.39
2	44303	15.14	12.95	11.72	10.12	8.49	7.14	5.80
3	50863	17.37	16.36	14.83	13.00	11.05	9.21	7.39
4	47110	70.62	47.33	24.08	13.81	9.17	6.70	5.13
5	50065	34.79	22.96	12.19	6.39	3.57	2.37	1.88
6	50292	26.98	18.96	15.25	12.51	10.15	8.24	6.60
7	50345	29.84	26.94	22.26	17.33	12.57	8.50	5.07
8	49885	29.77	24.46	17.76	12.64	8.37	5.97	4.03
9	49887	53.50	24.83	6.71	4.69	4.79	4.14	3.41
10	49820	26.02	23.71	19.94	15.73	11.59	8.48	6.00
11	50872	6.64	6.31	6.03	5.68	5.27	4.84	4.42
12	47063	83.49	61.13	34.41	19.34	12.38	9.62	8.04

(continued on next page)

TABLE 4 *(continued)*

DYNAFLECT DEFLECTIONS, MILS

SITE	MEAN FORCE LBS	D0 MEAN	D1 MEAN	D2 MEAN	D3 MEAN	D4 MEAN
1	1000	0.19	0.18	0.19	0.17	0.18
2	1000	0.25	0.24	0.23	0.18	0.18
3	1000	0.20	0.18	0.18	0.13	0.12
4	1000	0.64	0.45	0.30	0.19	0.14
5	1000	0.36	0.24	0.14	0.07	0.06
6	1000	0.32	0.27	0.25	0.19	0.16
7	1000	0.69	0.65	0.54	0.41	0.30
8	1000	0.34	0.32	0.23	0.14	0.10
9	1000	0.53	0.25	0.15	0.10	0.09
10	1000	0.38	0.36	0.29	0.20	0.15
11	1000	0.15	0.14	0.15	0.12	0.13
12	1000	1.11	0.83	0.54	0.34	0.27

DYNA FWD DEFLECTIONS, MILS

SITE	MEAN FORCE LBS	D0 MEAN	D1 MEAN	D2 MEAN	D3 MEAN	D4 MEAN	D5 MEAN	D6 MEAN
1	25485	4.43	3.48	3.53	3.02	3.34	2.73	2.99
2	25348	8.62	6.85	6.25	5.16	4.56	3.64	3.22
3	25093	8.68	8.05	7.46	6.43	5.66	4.57	3.85
4	24415	46.60	24.26	11.86	7.06	5.02	3.61	2.96
5	24870	19.76	10.90	5.30	2.53	1.53	1.01	0.99
6	25027	17.84	8.77	7.32	5.85	4.85	3.75	3.26
7	25347	13.17	11.93	9.87	7.57	5.53	3.54	2.19
8	25334	15.45	10.74	7.56	5.28	3.55	2.49	1.79
9	24632	38.43	12.69	2.76	2.24	2.37	1.85	1.79
10	25277	13.06	11.35	9.57	7.40	5.44	3.77	2.84
11	25763	3.15	2.92	2.85	2.63	2.55	2.17	2.13
12	24635	51.34	32.31	16.82	9.13	5.91	4.37	4.20

TABLE 4 *(continued on next page)*

TABLE 4 *(continued)*

ROAD RATER DEFLECTIONS, MILS

SITE	MEAN FORCE LBS	D0 MEAN	D1 MEAN	D2 MEAN	D3 MEAN
1	6740	0.95	0.67	0.73	0.58
2	6895	2.00	1.33	1.13	0.90
3	6925	2.63	1.63	1.33	1.20
4	6967	7.57	4.00	2.63	2.02
5	6965	3.38	1.00	0.50	0.35
6	6948	4.05	2.47	1.97	1.67
7	7003	5.62	3.82	2.87	2.10
8	6995	3.33	1.88	1.27	0.78
9	6935	5.00	1.13	0.75	0.67
10	6918	3.27	2.33	1.70	1.20
11	6985	1.42	0.90	0.82	0.77
12	6932	9.07	4.43	2.37	1.65

WES 16-KIP DEFLECTIONS, MILS

SITE	MEAN FORCE LBS	D0 MEAN	D1 MEAN	D2 MEAN	D3 MEAN
1	15013	2.13	1.17	1.61	1.46
2	14395	4.18	3.42	2.80	2.27
3	14494	4.24	3.35	2.67	2.19
4	15009	12.04	9.77	3.97	2.34
5	14474	6.31	5.07	1.84	1.07
6	15142	7.51	6.11	4.20	3.36
7	15093	10.07	8.46	6.07	4.35
8	14808	6.45	5.75	3.40	2.19
9	14827	10.02	7.08	2.49	2.13
10	14385	5.89	5.21	3.53	2.43
11	14535	2.69	1.97	1.84	1.69
12	14198	18.76	16.12	7.58	4.84

PHONIX DEFLECTIONS, MILS

SITE	MEAN FORCE LBS	D0 MEAN	D1 MEAN	D2 MEAN	D3 MEAN	D4 MEAN	D5 MEAN
1	19499	3.98	2.85	2.52	2.52	2.40	2.07
2	20392	6.93	5.35	4.77	4.10	3.47	2.95
3	20289	6.70	6.13	5.57	4.90	4.22	3.57
4	18881	35.88	19.13	9.35	5.37	3.73	2.87
5	19740	15.17	8.37	4.05	1.87	1.10	0.80
6	19808	14.17	6.85	5.57	4.60	3.72	3.07
7	19946	9.72	8.62	7.20	5.48	3.90	2.80
8	19190	11.35	7.80	5.38	3.72	2.45	1.88
9	18685	29.23	9.80	1.67	1.73	1.75	1.50
10	19877	9.13	7.80	6.45	5.00	3.65	2.77
11	19499	2.50	2.25	1.95	2.00	1.90	1.77
12	19156	40.03	25.47	13.25	6.58	4.37	3.53

TABLE 5 CBR TEST RESULTS

Location	Test Number	Measured CBR	Average CBR
	Site No. 4		
Top of base	1	90	88
	2	82	
	3	92	
Middle of base	1	93	100
	2	98	
	3	106	
	4	103	
Top of subgrade	1	15	16
	2	17	
	3	17	
	Site No. 5		
Top of base	1	60	77
	2	96	
	3	74	
Top of subgrade	1	44	46
	2	41	
	3	52	
16 in. into subgrade	1	20	25
	2	26	
	3	29	
	Site No. 9		
Top of base	1	47*	11
	2	11	
	3	10	
Top of subbase	1	50	40
	2	33	
	3	37	
Top of subgrade	1	14	16
	2	14	
	3	19	
14 in. into subgrade	1	29	32
	2	39	
	3	29	
	Site No. 12		
Top of base	1	111	117
	2	118	
	3	123	
Top of subgrade	1	15	13
	2	15	
	3	13	
14 in. into subgrade	1	3.9	4.3
	2	4.3	
	3	4.6	

* Test result discarded.

TABLE 6 MOISTURE AND DENSITY TEST RESULTS

Location	Nuclear Gage			
	Water Content	Dry Density	Wet Density	Oven Dry Water Content
Site No. 1				
Top of subgrade	*	*	*	10.9
Site No. 2				
Top of subgrade	*	*	*	**
Site No. 3				
Top of base	13.0	115	128	9.5
Top of subgrade	18.4	104	123	15.5
Site No. 4				
Top of base	11.2	128	138	8.2
Middle of base	10.1	125	135	6.4
Top of subgrade	18.3	108	126	14.5
Site No. 5				
Top of base	*	*	*	2.6
Top of subgrade	16.0	116	135	9.6
16 in. into subgrade	18.2	110	130	9.9
Site No. 6				
Top of subgrade	8.8	119	129	8.5
Site No. 7				
Top of subgrade	22.6	111	133	19.9
Site No. 8				
Top of subgrade	19.3	115	137	18.6
Site No. 9				
Top of base	8.7	130	134	3.0
Top of subbase	16.8	115	133	15.0
Top of subgrade	24.0	107	130	20.2
14 in. into subgrade	24.6	112	132	18.8
Site No. 10				
Top of base	13.8	111	131	17.9
Site No. 11				
Top of base	7.1	134	142	6.1
Site No. 12				
Top of base	3.8	143	147	3.1
Top of subgrade	18.2	109	127	15.7
14 in. into subgrade	*	96	*	21.6

* Test not conducted, or data inconsistent.

3-in.^{2} piston expressed as a percent of a standard. The standard is 1,000 psi at 0.1-in. penetration or 1,500 psi at 0.2-in. penetration. CBR tests are used to determine relative soil strengths. Tests were performed on each layer of the foundation below the asphalt surface. CBR values were also determined below the undisturbed sample that was extracted from the subgrade. CBR data for the asphalt surface sites are presented in Table 5.

Moisture and Density Tests

At each site location, moisture content and density tests were conducted. Density and moisture content data were collected on each layer of foundation material at each site. Densities were determined with the nuclear gauge on the granular materials and with drive cylinders of known volume on the fine-grained soils. Moisture contents were taken on all layers using the oven-dry sample method. Results of the moisture and density tests are presented in Table 6.

Plate Bearing Tests

Thirty-in.-diameter plate bearing tests were conducted on the surface of the subgrade beneath the slab at the PCC and composite pavement sites. A 40-ft-long flatbed trailer spanned the gap left by removing the 4- × 4-ft PCC surface. This trailer was loaded with 1-ton lead blocks against which the hydraulic ram would react to apply the necessary force to the 30-in.-diameter plate used in testing the subgrade. The plate bearing tests were conducted in accordance with MIL-STD-621A (*3*), Method 104. Plate bearing test results are presented in Table 7.

Laboratory Testing

The bag samples were tested to determine the soil classification using the Unified Soil Classification System. The results of these tests are presented in Table 8.

TABLE 7 PLATE BEARING TEST RESULTS

Site Number	Depth from Surface, in.	k* pci
1	18.0	294
3	10.0	303
6	17.5	476
7	7.0	82
8	13.5	27
10	9.0	192
11	21.0	82

* k = slope of average pressure versus deflection curve during loading.

TABLE 8 SUMMARY OF SOIL CLASSIFICATION TEST RESULTS

Site No.	Sample No.	Layer	Atterberg Limits LL	PL	PI	Specific Gravity	Percent Gravel	Percent Fines	Classification
1	1	Subgrade	NP	NP	NP	2.66	2	98	Silty sand (SM)
2	2	Subgrade	16	10	6	2.67	2	98	Clayey silty sand (SM-SC)
3	3	Base	NP	NP	NP	2.65	20	80	Gravelly silty sand (SP-SM)
3	4	Subgrade	NP	NP	NP	2.64	0	100	Silty sand (SP-SM)
4	5	Base	19	13	6	2.67	18	82	Gravelly silty sand (SM-SC)
4	6	Subgrade	NP	NP	NP	2.65	0	100	Silty sand (SP-SM)
5	7	Base	NP	NP	NP	2.65	76	24	Sandy gravel (GP)
5	8	Subgrade	44	16	28	2.68	1	99	Clayey sand (SC)
6	9	Subgrade	19	10	9	2.67	2	98	Clayey sand (SC)
7	10	Subgrade	33	15	18	2.72	8	92	Sandy clay (CL)
8	11	Subgrade	30	14	16	2.72	12	88	Gravelly sandy clay (CL)
9	12	Base	17	11	6	2.83	62	38	Sandy silty gravel (GP-GM)
9	13	Subgrade	35	16	19	2.73	32	68	Sandy clayey gravel (GC)
9	14	Subbase	35	15	20	2.74	26	74	Gravelly clayey sand (SC)
10	15	Base	33	15	18	2.69	--Sample contained asphalt--no tests--		
10	16	Subgrade	38	15	23	2.74	6	94	Sandy clay (CL)
11	17	Base	17	10	7	2.69	36	64	Gravelly silty sand (SP-SM)
11	18	Subgrade	23	11	12	2.69	2	98	Clayey sand (SC)
12	19	Base	15	10	5	2.71	47	53	Sandy silty gravel (GP-GM)
12	20	Subgrade	35	22	13	2.68	0	100	Sandy clay (CL)

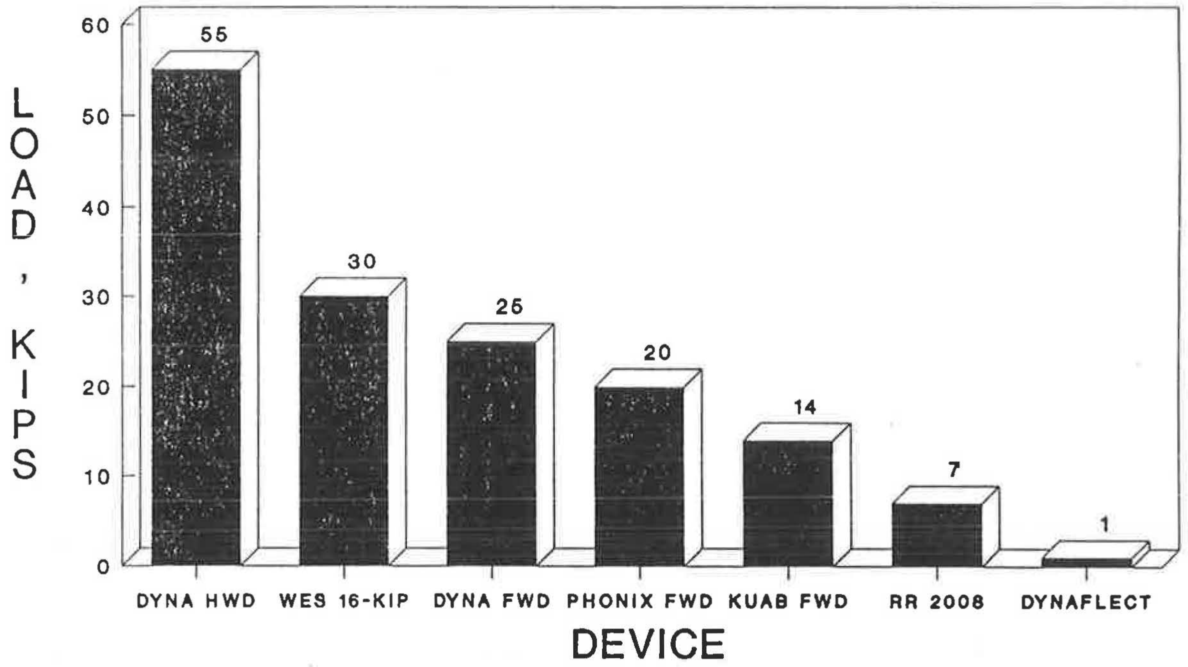


FIGURE 4 **Maximum load output for NDT devices.**

TABLE 9 SUMMARY OF INPUTS FOR BACKCALCULATION PROGRAM (BISDEF)

Site	No. of Layers	No. of Variable Layers	Layer 1, ksi			Layer 2, ksi			Layer 3, ksi		
			E min	E max	E in.	E min	E max	E in.	E min	E max	E in.
1	2	2	2500	7000	3500	1	75	20			
2	3	2			250*	2500	7000	3500	1	75	20
3	2	2	2500	7000	3500	1	75	20			
4	3	3	200	1000	350	5	150	30	1	75	20
5	3	2			250*	5	150	30	5	70	25
6	3	2			200*	2500	7000	3500	1	75	20
7	2	2	2500	7000	3500	1	75	20			
8	3	2			150*	1000	7000	2500	1	75	20
9	3	2			250*	5	150	30	1	75	20
10	3	2			200*	2500	7000	2500	1	75	20
11	2	2	2500	7000	3500	1	75	20			
12	3	3	100	1000	250	5	150	30	1	75	20

* Fixed modulus.

Backcalculation of Moduli

The BISDEF program (*4*) was used to backcalculate moduli values for each pavement using deflection basins from each device during the replicate testing. Deflection basins from the maximum loads (Table 3 and Figure 4) were selected for analysis. Because variability in the first drop was noted during the short-term repeatability tests, only the last two tests of each of the three replicates were analyzed. Therefore, a total of six tests for each device were used in the backcalculation. Results for subgrade modulus values are presented in Tables 8 through 10. Subgrade modulus is presented because for other pavement layers the moduli were either fixed or were calculated at a predetermined limit. The NDT equipment malfunctioned in some cases and only four basins were recorded.

The BISDEF program uses the BISAR (*5*) elastic layer program to calculate deflections. The pavement system is described by layers that can be of fixed or variable moduli. For variable layers, a minimum, a maximum, and an initial starting moduli are defined. For the analysis presented herein, the 12 pavement sites were described as shown in Table 8. The asphalt surface moduli were fixed on Sites 2, 5, 6, 8, 9, and 10. All other layers for each site were allowed to vary between the ranges given in Table 9.

A rigid layer was placed at 20 ft below the surface for these modulus calculations. The procedure is limited to knowing where a rigid layer exists. The elastic solution is best represented when reasonably accurate modulus values are selected for those layers that are held constant and the elastic solution for the variable layers is within the maximum and minimum values selected. The BISDEF program will accurately find the best elastic solution for up to three variable layers. This solution may not be acceptable because pavements are not linearly elastic mediums.

The SPSS statistical analysis program (*6*) was used for analysis of variance. For all 12 pavement sites, the differences in moduli were found to be significant.

To compare the differences, bar charts will be presented. Subgrade modulus results are shown in Figure 5 for the impulse load devices on AC sites. The devices are plotted in order of decreasing load magnitude. Generally, the modulus increases with load, indicating that the subgrade materials are stress dependent (i.e., the modulus decreases with increased stress).

Subgrade modulus values for vibrators on the AC sites are shown in Figure 6. Again, they are plotted in order of decreasing load magnitude. The increase in modulus with decrease in load applies for the WES 16-kip and the Dynaflect. The Road Rater values appear to be highly variable. All devices are shown in Figure 7. They are plotted in order of decreasing load magnitude. The WES 16-kip modulus values are significantly lower on the two pavements on the right in Figure 7. These sites are fine-grained soil that should be more stress

TABLE 10 BACKCALCULATED SUBGRADE MODULI FOR ASPHALT PAVEMENTS

	Site 5			Site 4		
	Count	Mean KSI	Standard Deviation	Count	Mean KSI	Standard Deviation
KUAB	6	58.3	1.454	6	23.3	0.668
DYNA HWD	6	54.1	0.203	6	20.7	0.075
DYNAFLECT	6	69.8	0.471	4	29.6	0.944
DYNA FWD	6	61.1	1.005	6	19.9	0.095
ROAD RATER	4	70.0	0.059	6	16.1	4.291
WES 16-KIP	6	55.3	0.863	4	26.9	0.606
PHONIX	6	67.7	0.824	6	20.9	0.478

	Site 12			Site 9		
	Count	Mean KSI	Standard Deviation	Count	Mean KSI	Standard Deviation
KUAB	6	18.6	0.151	6	58.4	2.310
DYNA HWD	6	14.5	0.049	6	58.4	0.613
DYNAFLECT	6	15.7	0.068	6	45.7	13.877
DYNA FWD	6	15.6	0.304	6	46.1	0.892
ROAD RATER	6	19.0	1.221	6	49.6	3.636
WES 16-KIP	6	11.9	0.196	6	26.1	2.900
PHONIX	6	17.5	0.412	6	54.5	0.454

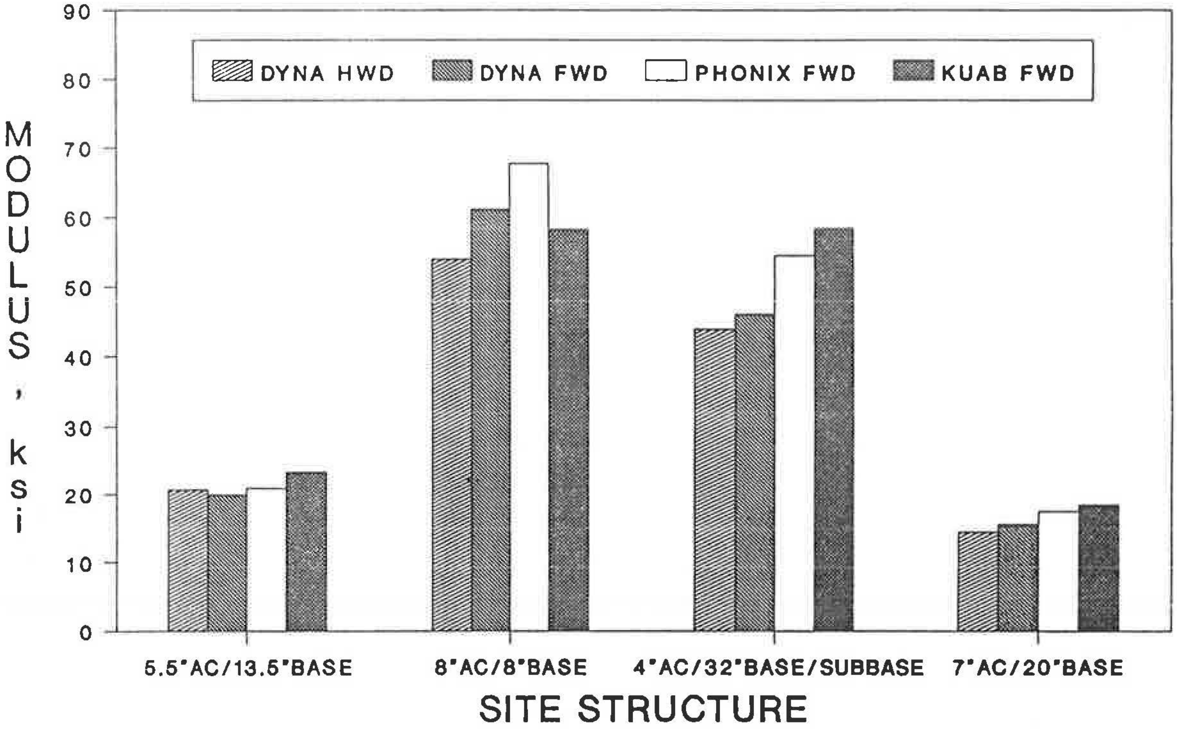


FIGURE 5 Backcalculated subgrade moduli for AC sites with FWDs.

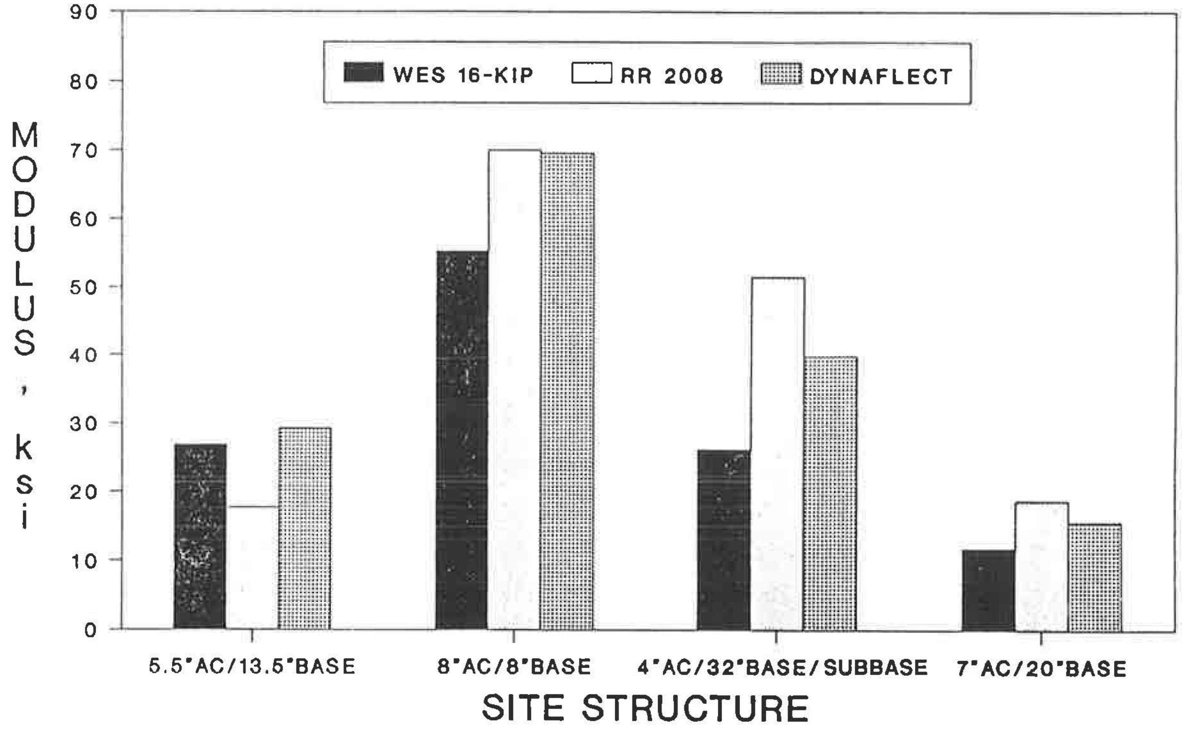


FIGURE 6 Backcalculated subgrade moduli for AC sites with vibrators.

sensitive than the coarse-grained sands of the other pavements. The WES 16-kip applies a 16,000-lb preload to the pavement. This preload on a stress-dependent subgrade may account for the lower modulus values.

The modulus values for the PCC sites from the impulse load devices data are shown in Figure 8. The modulus values generally increase with decreased load except for the lighter device, the Kuab. The Kuab modulus values appear to be variable.

The subgrade modulus values for the vibrators on PCC pavements are shown in Figure 9. On thick PCC pavement, the Dynaflect values are significantly lower than either the

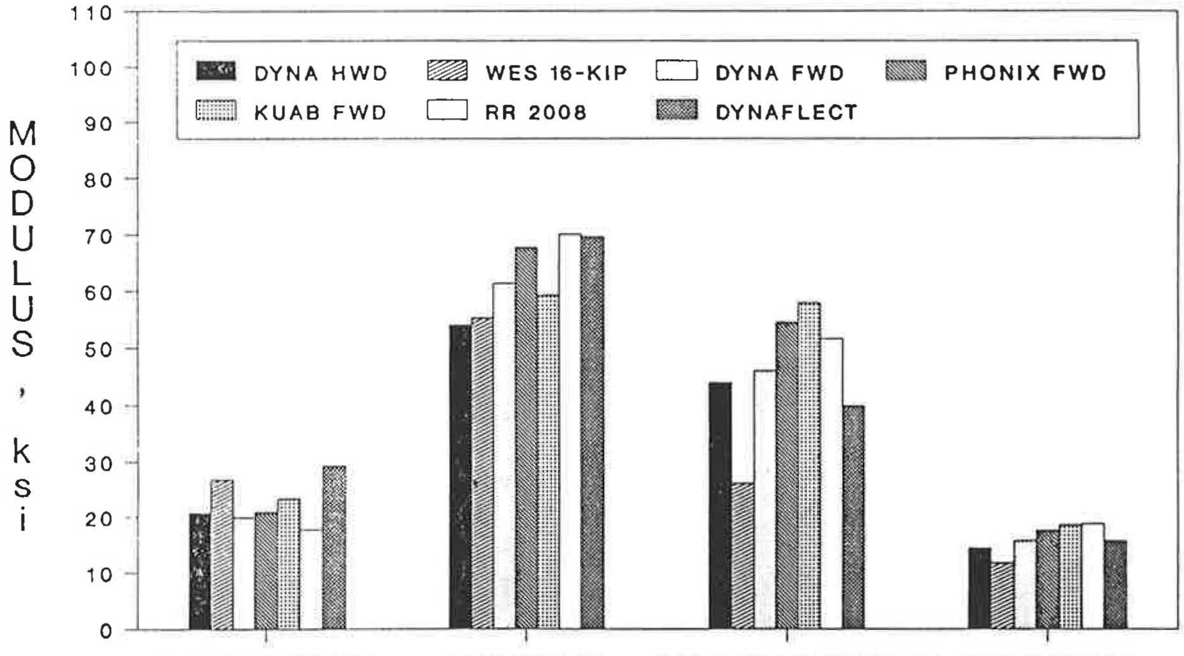


FIGURE 7 **Backcalculated subgrade moduli for AC sites.**

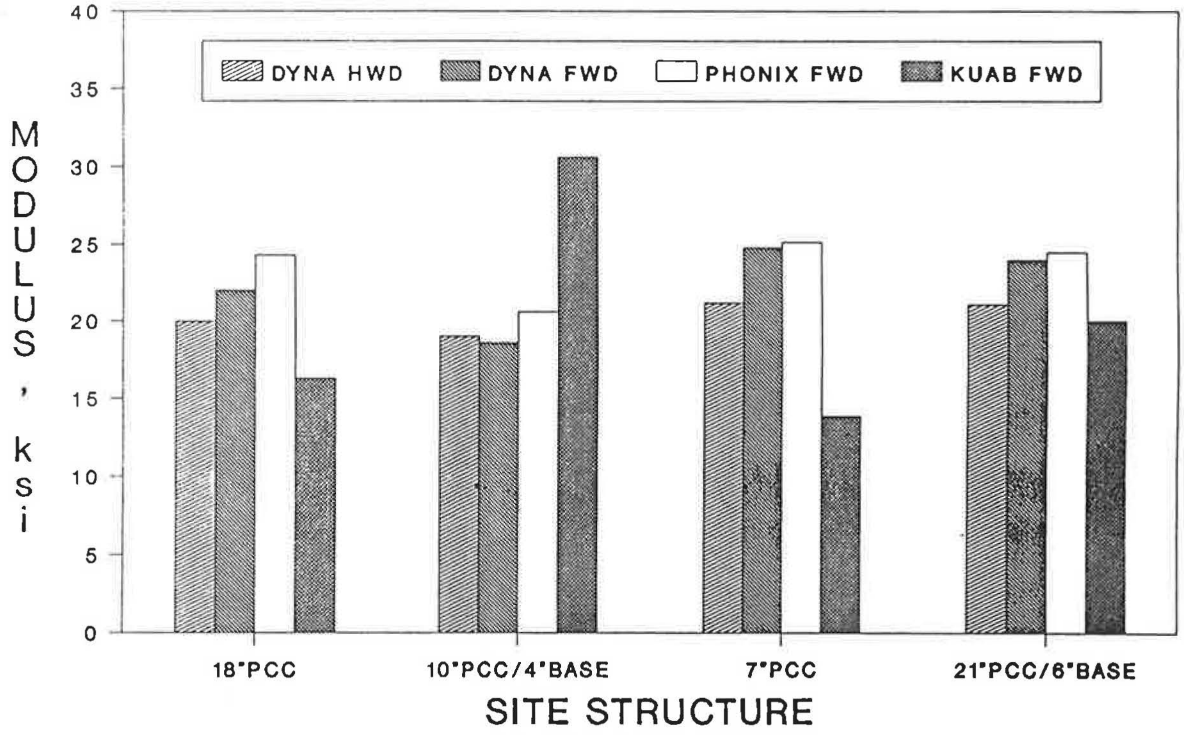


FIGURE 8 **Backcalculated subgrade moduli for PCC sites with FWDs.**

WES 16-kip or the Road Rater. The light load (1,000 lb_f) of the Dynaflect may not seat the thick PCC slabs and the deflections may be from only movement of the slab and not the pavement system. This stiffness reversal was also shown in the MacDill study (*1*).

Results from all devices on PCC pavements are shown in Figure 10. The Dynaflect values are significantly lower on the thick pavements. The WES 16-kip values are higher for the pavement plotted on the left of the figure that has a sand subgrade. Granular materials should increase in modulus with increase in confining stress. The confining stress would increase with the higher preload of the WES 16-kip.

Composite pavement subgrade moduli from the FWDs are shown in Figure 11. Again, the higher loads give lower moduli

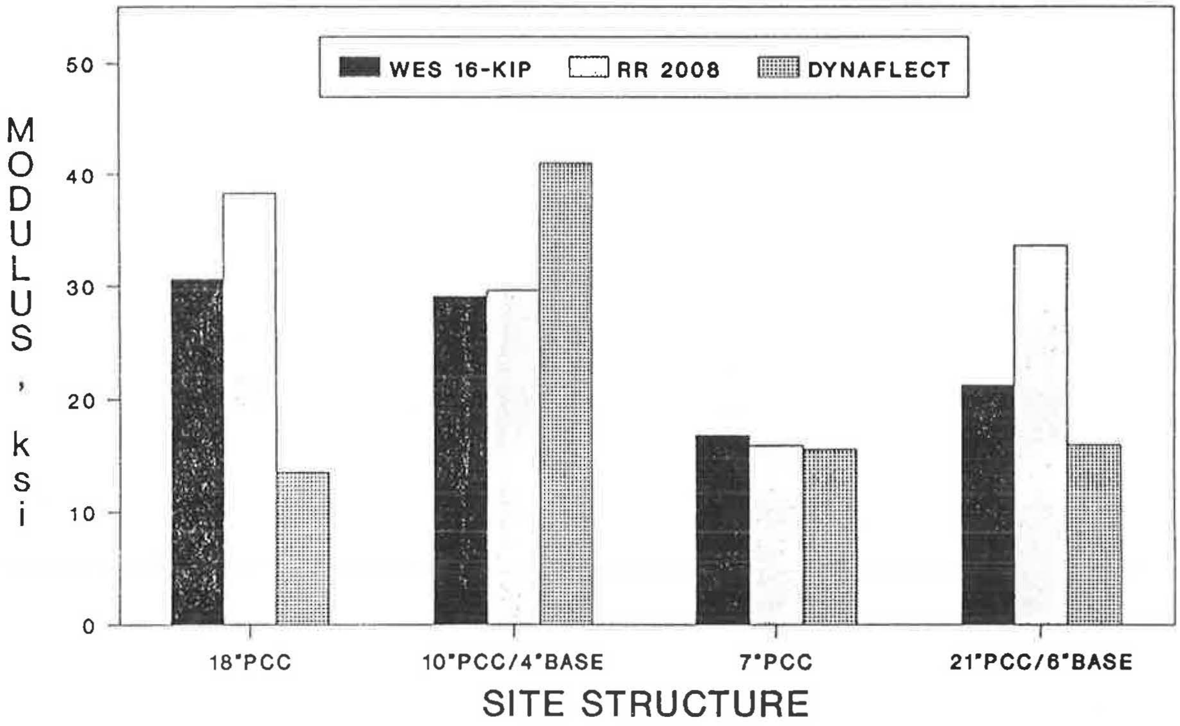


FIGURE 9 Backcalculated subgrade moduli for PCC sites with vibrators.

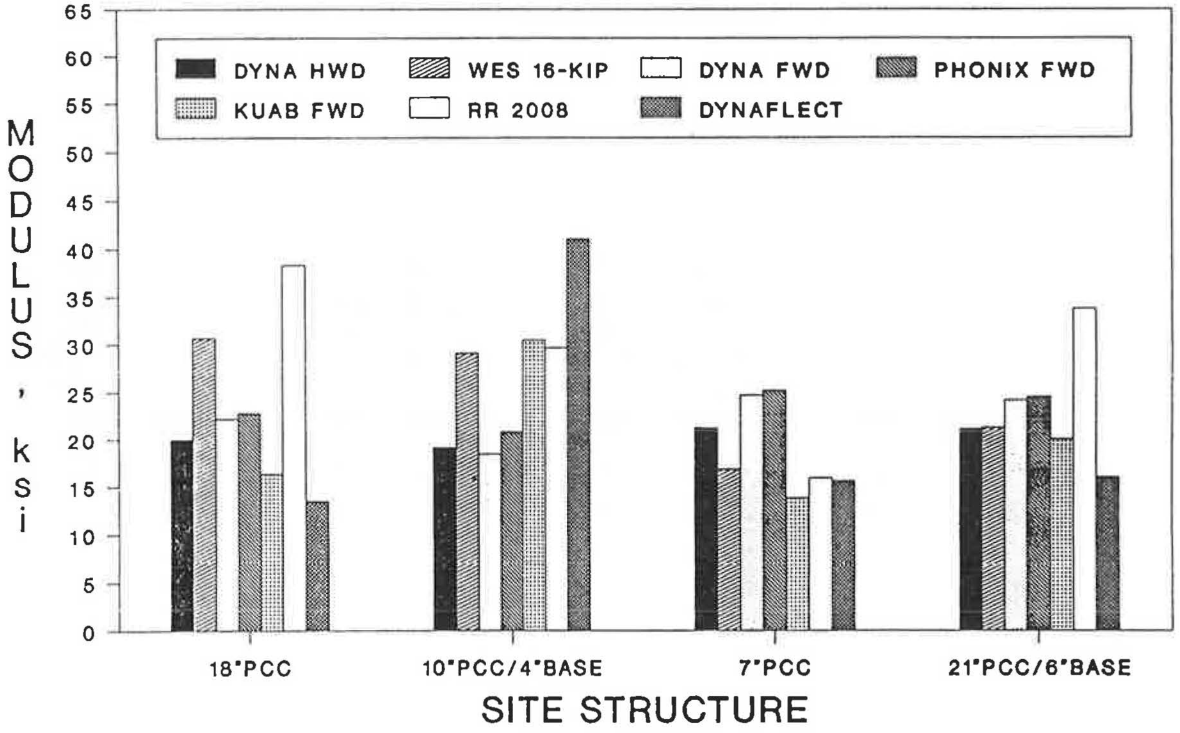


FIGURE 10 Backcalculated subgrade moduli for PCC sites.

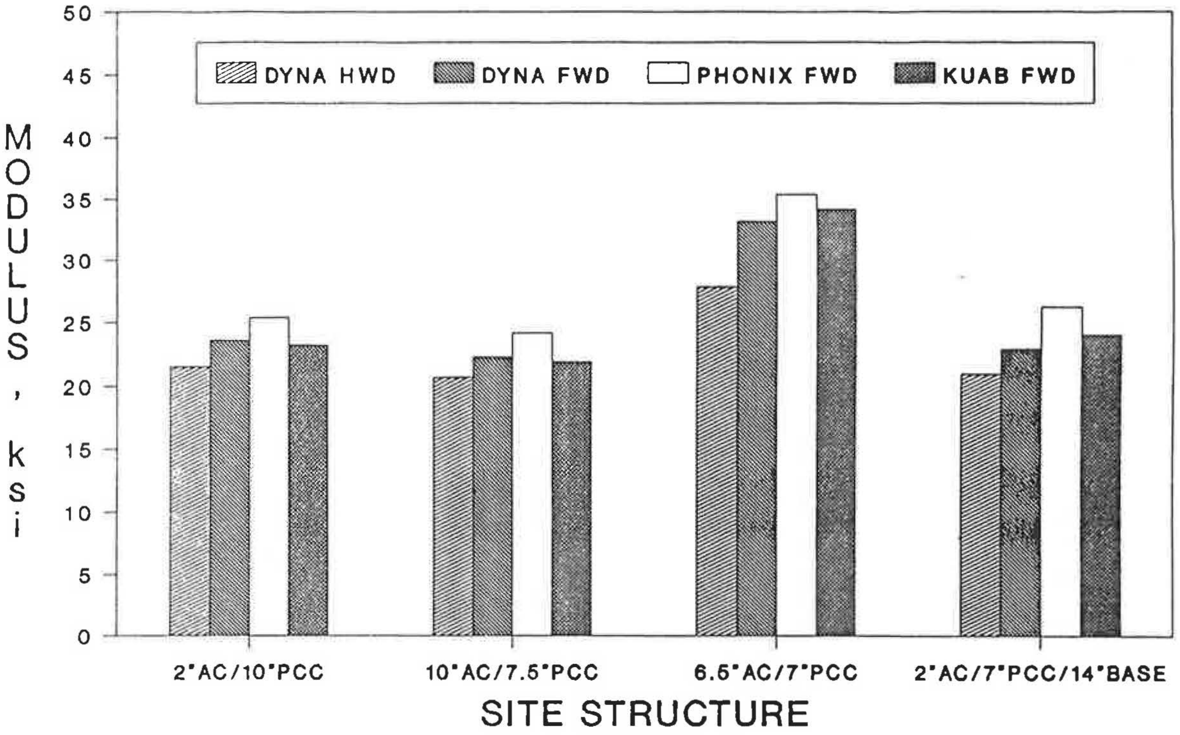


FIGURE 11 Backcalculated subgrade moduli for composite sites with FWDs.

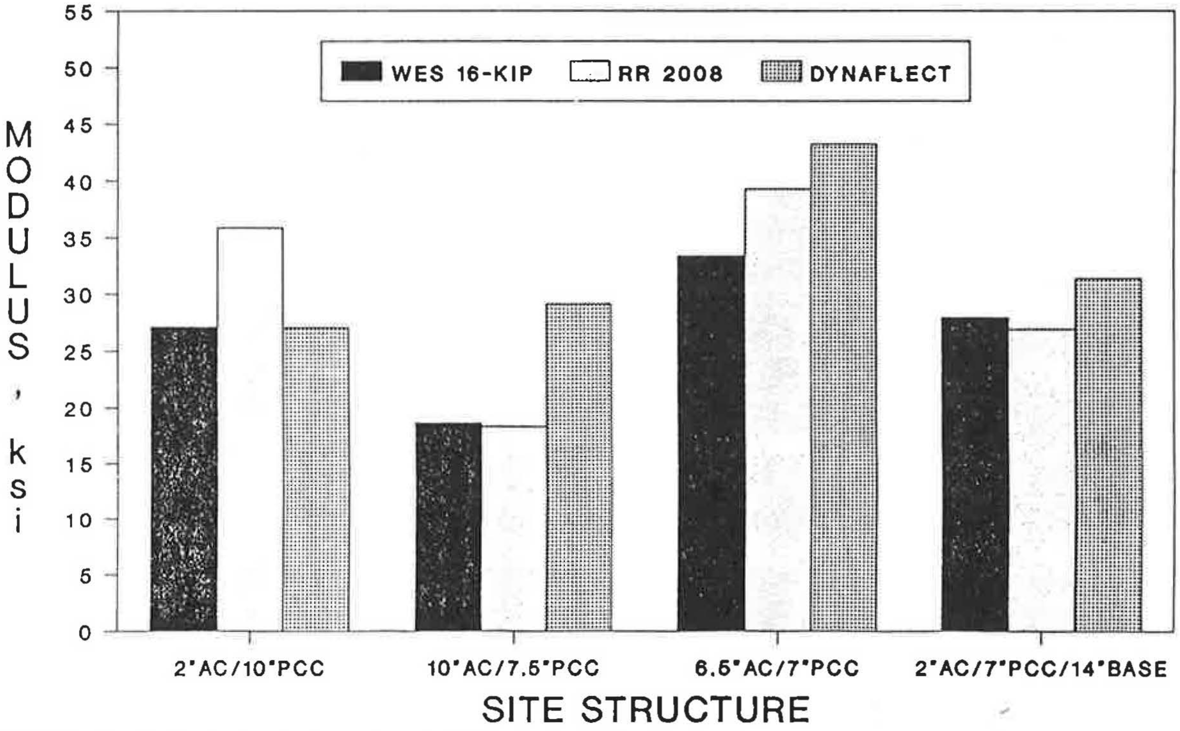


FIGURE 12 Backcalculated subgrade moduli for composite sites with vibrators.

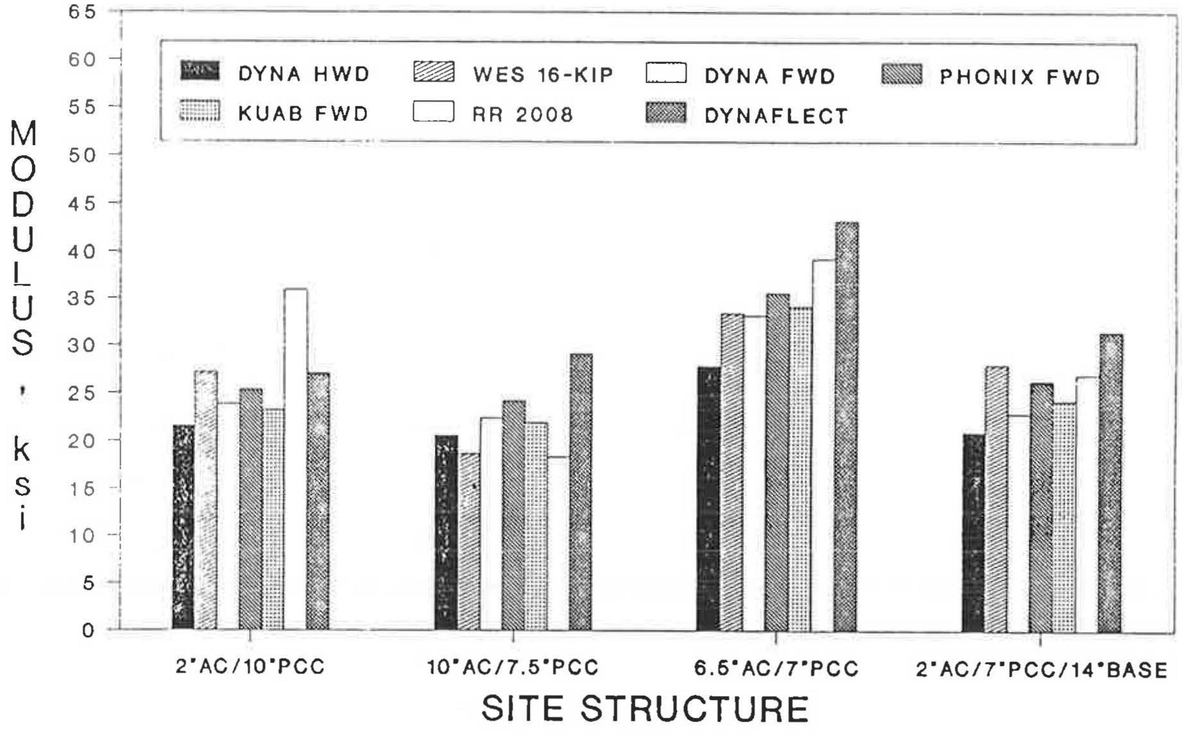


FIGURE 13 Backcalculated subgrade moduli for composite sites.

with the exception of the Kuab. Vibrator subgrade values on composite pavements are shown in Figure 12. Again the Road Rater appears to be highly variable. Modulus values for all devices are shown in Figure 13 for the composite pavements. For the composite pavements, the Dynaflect values are significantly larger than those for the other devices.

Allowable Load and Overlay Requirements

To define how the variability in subgrade moduli translates to allowable aircraft load and rehabilitation requirements, average pavement thicknesses were selected in a sensitivity analysis. The pavement parameters are as follows:

Design Aircraft: DC–10
Design Load: 590 kips
Design Passes: 100,000

	AC			*PCC*			*Composite*		
	E	*μ*	*H*	*E*	*μ*	*H*	*E*	*μ*	*H*
Layer 1	300	0.35	5	6000	0.15	10	300	0.35	5
Layer 2	40	0.35	12	Variable	0.4	—	6000	0.15	8
Layer 3	Variable	0.4	—				Variable	0.4	—

where

E = layer moduli (ksi),
μ = Poisson's ratio, and
H = layer thickness (in.).

The AIRPAVE program (*4*) was used to calculate the allowable aircraft loads and overlay thickness requirements for the DC–10 aircraft for these pavements with variations of the subgrade moduli. Results are shown in Figures 14 through 16 for each of the pavements. Overlay calculations are for AC overlays on AC and composite pavements and PCC overlays for PCC pavements. For the AC pavement, change in overlay thickness requirements and AGAL is very small when the subgrade modulus is greater than 20,000 psi. This is because the strain in the bottom of the AC layer controls on this pavement rather than the vertical strain in the subgrade.

Using the moduli data from Tables 10 through 12 and Figures 14 through 16, maximum variations in AGAL and overlay thicknesses for a single pavement site can be determined. These are as follows:

Pavement Type	*Range in AGAL for DC–10 (kips)*	*Range in Overlay Thickness (in.)*
AC	239 to 344	6.5 to 10.6
PCC	264 to 373	11.3 to 17.0
Composite	294 to 350	13.3 to 15.9

From this analysis, the maximum variation in overlay thickness requirement is about 4 in. of AC or 6 in. of PCC. These ranges are approximations but do indicate that different devices can give significant differences in rehabilitation requirements. These differences are significant in terms of construction costs.

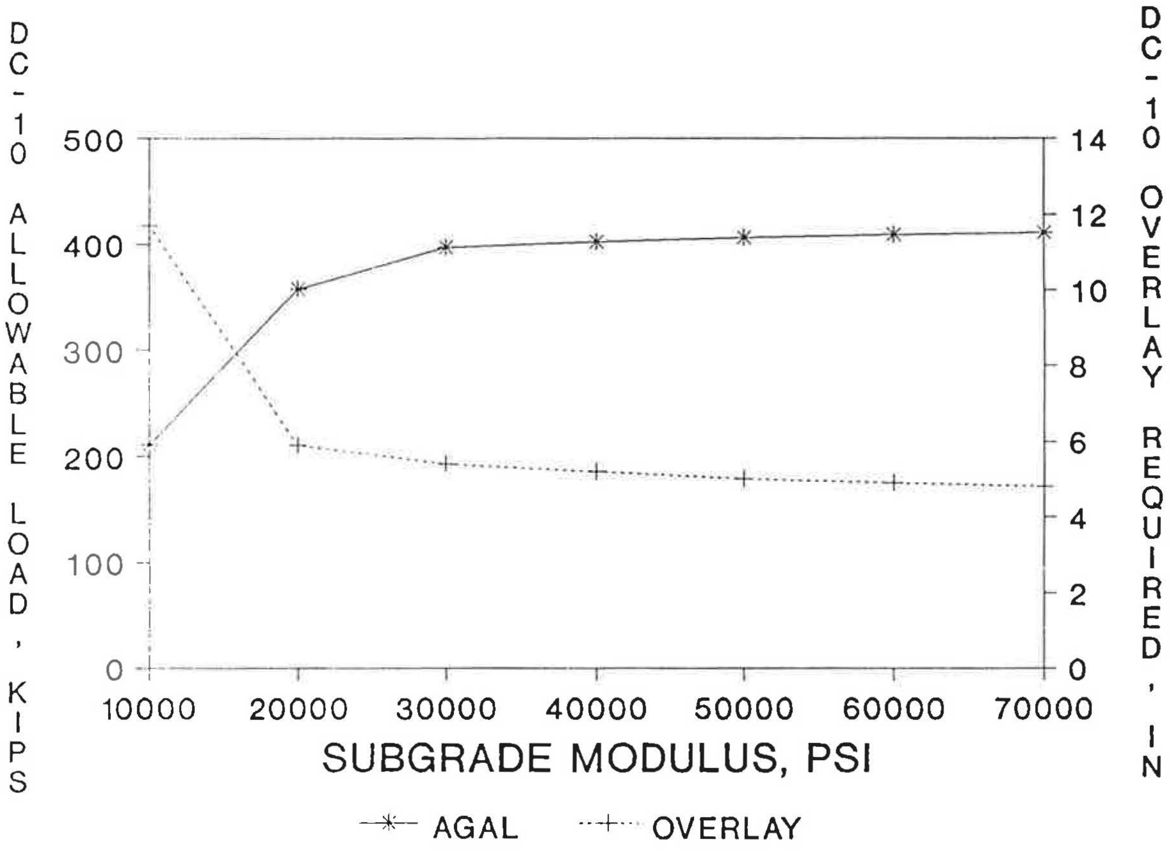


FIGURE 14 Allowable gross aircraft loads and overlay thickness requirements for asphalt pavements.

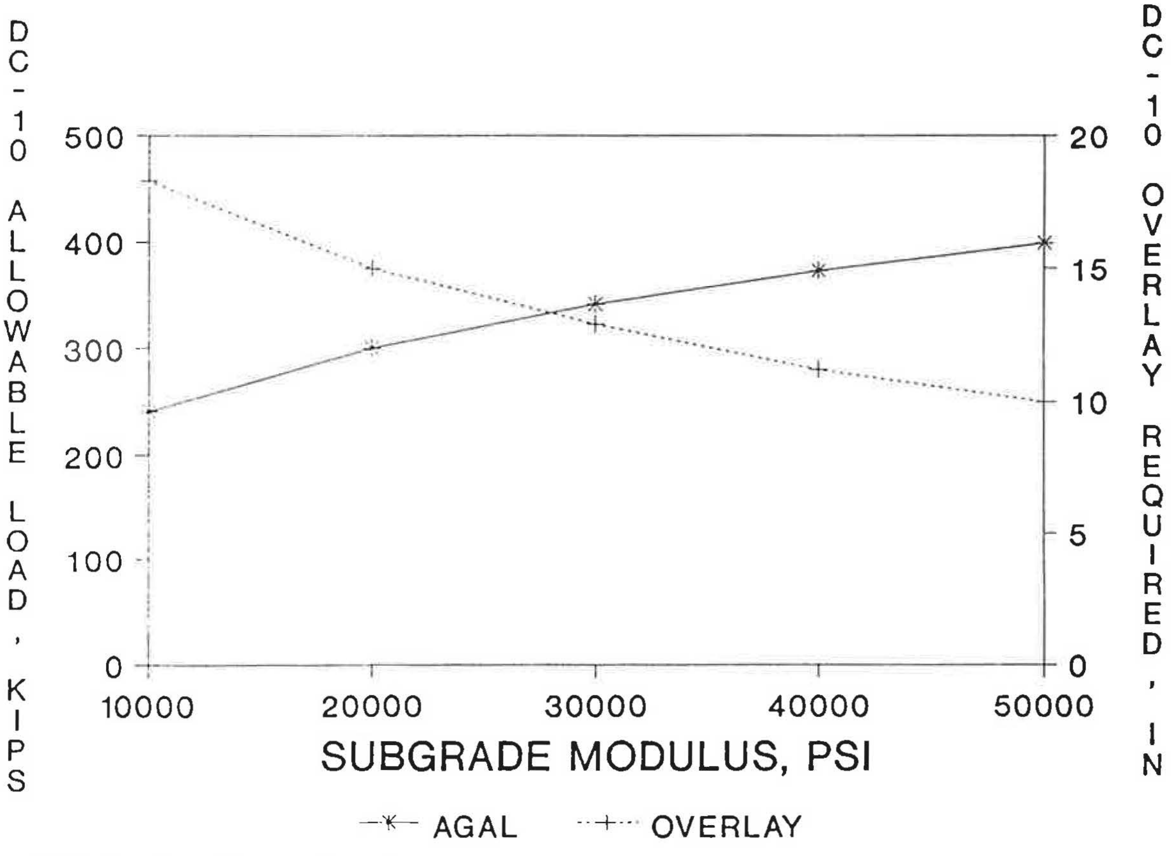


FIGURE 15 Allowable gross aircraft loads and overlay thickness requirements for PCC pavements.

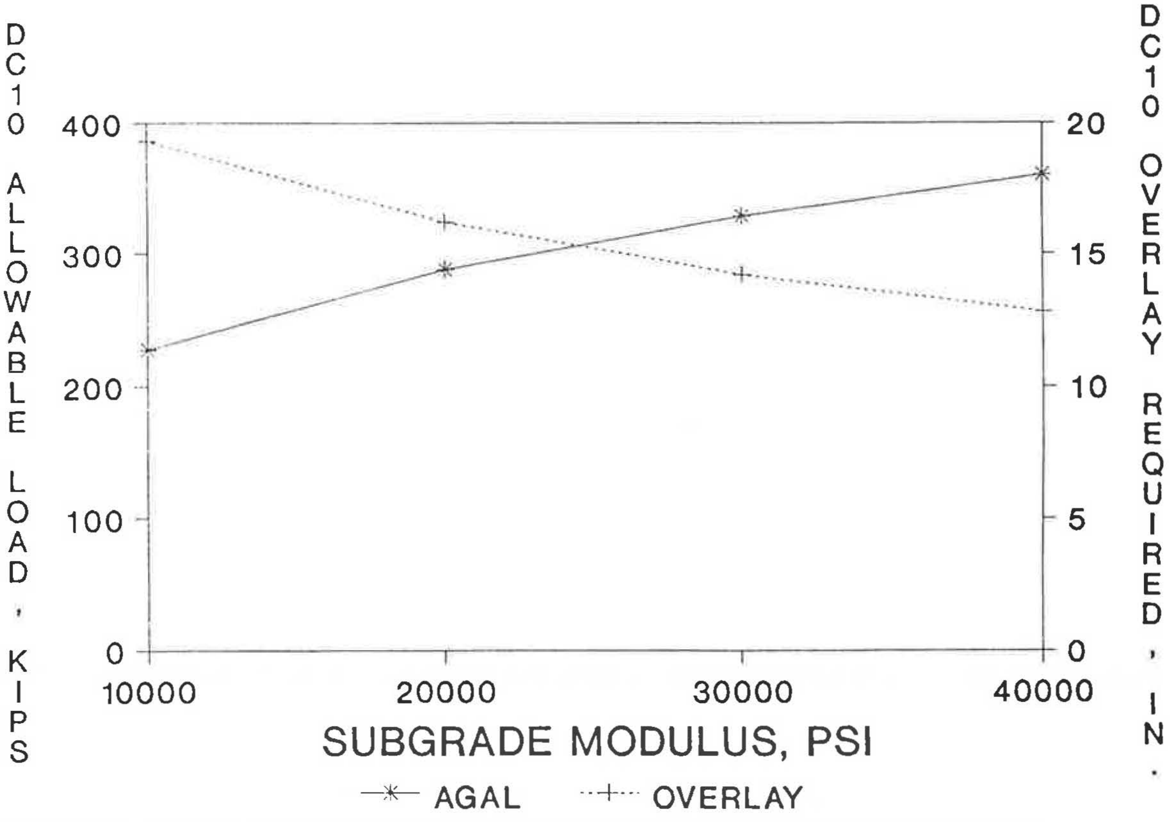


FIGURE 16 Allowable gross aircraft loads and overlay thickness requirements for composite pavements.

TABLE 11 BACKCALCULATED SUBGRADE MODULI FOR PORTLAND CEMENT CONCRETE PAVEMENTS

	Site 1			Site 3		
	Count	Mean KSI	Standard Deviation	Count	Mean KSI	Standard Deviation
KUAB	6	16.3	0.315	6	30.6	0.498
DYNA HWD	6	20.0	0.077	6	19.0	0.191
DYNAFLECT	6	13.7	0.384	6	40.8	1.651
DYNA FWD	6	22.0	1.467	6	18.6	0.640
ROAD RATER	6	39.1	6.264	6	29.6	0.559
WES 16-KIP	4	30.6	2.231	6	28.9	0.325
PHONIX	6	24.3	3.755	6	20.6	1.028

	Site 11			Site 7		
	Count	Mean KSI	Standard Deviation	Count	Mean KSI	Standard Deviation
KUAB	6	20.0	1.680	6	13.9	0.483
DYNA HWD	6	21.1	0.114	6	21.2	0.206
DYNAFLECT	6	16.1	0.923	6	15.5	0.403
DYNA FWD	6	24.0	0.528	6	24.8	0.660
ROAD RATER	6	33.1	8.849	6	15.9	1.198
WES 16-KIP	6	21.4	2.840	6	16.8	0.328
PHONIX	6	24.5	0.370	6	25.1	0.435

TABLE 12 BACKCALCULATED SUBGRADE MODULI FOR COMPOSITE PAVEMENTS

	Site 6			Site 2		
	Count	Mean KSI	Standard Deviation	Count	Mean KSI	Standard Deviation
KUAB	6	22.0	0.334	6	23.2	0.860
DYNA HWD	6	20.7	0.119	6	21.5	0.170
DYNAFLECT	6	28.8	0.890	6	27.1	0.546
DYNA FWD	6	22.3	0.400	6	23.6	0.412
ROAD RATER	6	18.4	0.837	6	35.9	2.658
WES 16-KIP	6	18.7	0.108	6	27.1	0.345
PHONIX	6	24.2	0.210	6	25.4	0.565

	Site 8			Site 10		
	Count	Mean KSI	Standard Deviation	Count	Mean KSI	Standard Deviation
KUAB	6	34.2	1.263	6	24.0	0.719
DYNA HWD	6	27.9	1.100	6	20.9	0.240
DYNAFLECT	6	43.1	0.977	6	31.2	0.744
DYNA FWD	6	33.1	0.936	6	22.9	0.146
ROAD RATER	6	39.3	5.064	6	27.0	0.388
WES 16-KIP	6	32.8	1.401	6	27.9	1.329
PHONIX	6	35.4	1.596	6	26.2	0.797

CONCLUSIONS

On the basis of preliminary analysis of data from seven NDT devices on 12 airfield pavements, the following conclusions are presented:

1. When conducting tests with an FWD, the first drop results are sometimes erroneous and should always be discarded.
2. The deflections and backcalculated moduli are highly variable from the Road Rater device.
3. The backcalculated moduli from the Kuab device does not follow the patterns of the other FWDs.
4. The variation in subgrade moduli from the seven devices results in significant differences in allowable aircraft load and overlay thickness requirements.

ACKNOWLEDGMENTS

The author gratefully acknowledges the support of the U.S. Army Engineer Waterways Experiment Station (WES) and the project sponsors, the U.S. Air Force Engineering and Services Center, the Naval Facilities Engineering Command, the FAA, and the Department of the Army, Office of Chief of Engineers. Permission was granted by the Chief of Engineers to publish this paper.

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Publication of this paper sponsored by Committee on Strength and Deformation Characteristics of Pavement Sections.