Analysis of Nondestructive Test Data on Flexible Pavements Acquired at the National Airport Pavement Test Facility

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Abstract

Nondestructive tests (NDT) were performed at various times on flexible pavement test items at the Federal Aviation Administration's (FAA) National Airport Pavement Test Facility (NAPTF) located at the William J. Hughes Technical Center, Atlantic City International Airport, New Jersey. The NDTs were performed with both falling weight deflectometer (FWD) and heavy falling weight deflectometer (HWD) equipment to document the uniformity of pavement and subgrade construction, as well as to acquire data on pavement response over time and increasing numbers of full-scale load repetitions.

Since the pavements and subgrades were constructed to exacting standards of uniformity and the NDTs were performed on pavements of known and uniform thicknesses, this enabled the backcalculated subgrade moduli under flexible pavements to be correlated against conventional test results. The FAA's new backcalculation software, FAABACKCAL, was used to process the NAPTF NDT data.

This paper discusses the evaluation of the NDT and other test data with respect to:

- Description of the FAA's new backcalculation software, FAABACKCAL.
- Linearity in pavement response and backcalculated subgrade modulus with applied HWD force.

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- Comparison of the stiffnesses of conventional and stabilized-base pavements on the same subgrade and like pavements on different subgrades.
- Relationship between in situ California Bearing Ratio (CBR) and backcalculated subgrade modulus for low-, medium-, and high-strength subgrade.
- The effect of the stiffness of underlying layers on backcalculated subgrade modulus.

Introduction

The subgrade and pavement test items at the NAPTF were constructed to exacting standards of uniformity. This was necessary to support the FAA's research on airport pavement failure criteria and comparative effects of four-wheel and six-wheel aircraft landing gears on the test pavements. For low- and medium-strength subgrades, clayey materials were imported and placed in 200-mm (8-inch) lifts to controlled depths of 3.7 m (12 ft.) and 3 m (10 ft.), respectively, below the pavement surface. The materials, taken from off-site borrow pits, were processed and moisture and density were carefully controlled to achieve uniform support conditions for construction of pavement test items (McQueen, 2000). CBR tests were performed at random locations on each lift of subgrade to control and document the CBR horizontally and vertically. In situ sandy materials were processed and placed to a controlled depth of 2.8 m (9 ft.) for the high-strength subgrade. The result was a controlled subgrade constructed with both cohesive and noncohesive soils, having nominal CBRs of 4, 8, and 25 for low-, medium-, and high-strength subgrades, respectively. The flexible and rigid pavement test items were constructed to equally exacting quality standards on each controlled subgrade.

To document the uniformity of the subgrade and pavement construction and to obtain data to support the FAA's airport pavement research objectives, nondestructive tests were performed at different times using FWD and HWD NDT equipment. Pavement and subgrade moduli were backcalculated from the HWD data using the FAA's new FAABACKCAL backcalculation software. Since the NDTs were performed on test pavements and subgrades having known properties, this has provided the FAA with a unique opportunity to analyze the NDT results as an initial step in establishing possible future standards for nondestructive testing of airport pavements.

Since the FAA's conventional and layered elastic design methods for flexible pavements are essentially based on subgrade CBR (FAA, 1995) or correlation to subgrade CBR (Barker, et al., 1975), respectively, it is important to establish correspondence between the subgrade modulus backcalculated from the NDT and in situ CBR data.

This would enable NDT results to be used directly in current and future FAA design procedures for flexible airport pavements.

FWD and HWD tests performed at varying load levels would also enable evaluation of the effect of increasing load levels on pavement response and backcalculated subgrade modulus. Evaluation of the linearity of pavement response and backcalculated subgrade modulus with load could also be used to specify minimum requirements for NDT equipment for airport pavements. Finally, since the subgrades were placed to known depths, the effect of changes in subgrade layer stiffness at depth could be demonstrated.

This paper discusses the evaluation of NAPTF NDT data for flexible pavements. (Guo, et al., 2001) discuss the evaluation of NAPFT NDT data for rigid pavements. Also, since current FAA conventional and layered elastic design methods require subgrade strength as the design input with defaults used for pavement layers, the NDT data analysis summarized herein mainly concentrated on subgrade modulus.

Test Pavement Construction

Flexible test pavements at the NAPTF were constructed on low-, medium-, and high-strength subgrades having nominal CBRs of 4, 8, and 25, respectively. The subgrade CBR data, along with data on test location, density, compaction, and moisture content are contained in the FAA's materials database. The database also records pavement thicknesses and contains data on pavement materials properties. The subgrade was constructed in controlled lifts of approximately 200 mm (8 inches) to the depths shown in Figure 1 (McQueen, 2000).

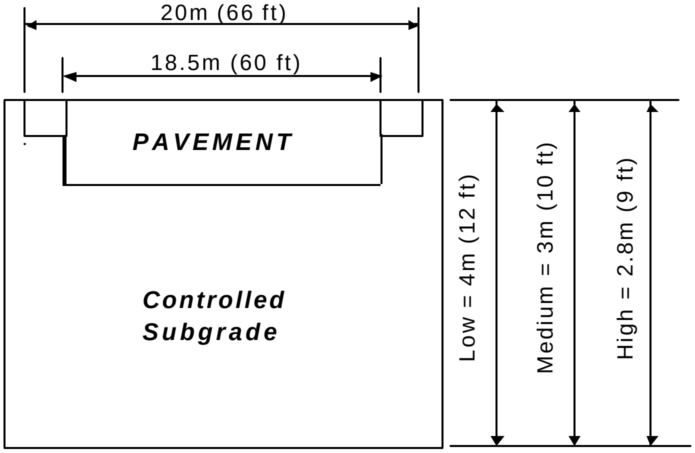

Figure 1. NAPTF typical cross section.

Low- and medium-strength subgrades were constructed with imported soils conforming to Unified Soil Classification of ML/CL and CH, respectively. High-strength soils and the soils beneath the controlled low- and medium-strength subgrades consisted of the native SP/SM soils.

Table 1 contains the average CBR results for all subgrade layers for the full depth of subgrade construction and the average CBR results of the top 30 cm (12 inches) of subgrade recorded during subgrade construction. These data were extracted from the FAA's materials database.

Table 1. Initial CBR results.

Subgrade	Average CBR (%) All Layers	Average CBR (%) Top 30 cm (12 in.)
Low	3.9	3.3
Medium	9.3	8.5
High	35.8	29.5

Just prior to the initiation of full-scale tests or about 6 months after the initial construction, test pits were opened to a depth of 1.2 m (4 ft.) to 1.5 m (5 ft.) below the surface of flexible pavements on stabilized base. CBR and other tests were performed at several depths into the subgrade. The CBR results for all layers and the top 30 cm (12 inches) are summarized in Table 2.

Table 2. Test pit CBR results.

Subgrade	Average CBR (%) All Layers	Average CBR (%) Top 30 cm (12 in.)
Low	5.0	5.3
Medium	6.1	7.0
High	45.1	33.8

Nondestructive Tests

After completing pavement construction, NDTs were performed by Engineering & Research International (ERI) with a KUAB Model 150 FWD. The FWD was used while awaiting delivery of the FAA's HWD equipment. Tests were performed at nominal force amplitudes of 40 kN (9,000 lbs.), 60 kN (13,500 lbs.), 82 kN (18,500 lbs.), and 115 kN (25,900 lbs.). A 30-cm (12-inch) segmented load plate was used during this test sequence and response measured with seven seismometers spaced at 30 cm (12 inches). Tests were conducted over six lanes at nominal offsets of 1.5, 4.5, and 7.5 meters (5, 15, and 25 ft.) left and right of centerline at 6 m (20 ft.) spacings.

A KUAB Model 240 HWD was later purchased by the FAA and used for all subsequent NDTs. The HWD equipment is described by (Guo, et al., 2001). The HWD tests at test pit locations were conducted with a 45-cm (18-inch) segmented load plate at nominal force amplitudes of 53 kN (12,000 lbs.), 106 kN (24,000 lbs.), and 160 kN (36,000 lbs.). NDTs were performed with the HWD before and after opening the pretraffic test pits at locations immediately adjacent to the test pits. The HWD also used seven seismometers at 30-cm (12-inch) intervals for recording response data.

For the purpose of this study, only the initial FWD data and HWD data at test pit locations were used, since companion conventional test data on subgrade were available for these tests. However, the FAA is conducting HWD tests on an on-going basis to support their research objectives. FWD and HWD data files can be downloaded from the FAA Airport Technology Branch's web site: www.airporttech.tc.faa.gov.

Backcalculation Software

The software used to backcalculate FWD and HWD data was developed under the sponsorship of the FAA Airport Technology Branch and is based on the LEAF layered elastic computation program.

The backcalculation software, FAABACKCAL, was written in Visual Basic 6.0 and uses LEAF to compute deflection basins for a specified structure. Pavement layer and subgrade elastic moduli are adjusted to minimize the root mean square (rms) of the differences between the sensor measurements and the computed deflection basin. A standard multidimensional simplex optimization routine is used to adjust the layer moduli values. The program reads FWD and HWD files in raw format. The user can then select any deflection basin from the FWD or HWD file. Sensor spacing, plate radius, and plate loading (force) are automatically read for the selected deflection basin. The program output consists of elastic moduli for each layer in the pavement section. Measured and calculated deflection basins are also included in the output along with the number of iterations and the value of the rms function.

The FAABACKCAL program was enhanced for this work to include the capability of batch computations. FWD or HWD data can be processed in a batch, allowing the user to backcalculate an entire FWD file in a matter of minutes. The output file contains all of the backcalculated basins along with the rms function, the number of iterations, and the elastic moduli for each layer. A separate program automatically imports the output file to a commercial spreadsheet program.

The results obtained with the FAA's backcalculation program were compared to other backcalculation software such as WESDEF. The comparison showed minimal difference between the backcalculated sets of moduli.

A stiff layer was defined at a depth were the native soil meets the constructed subgrade. For the low-strength subgrades, the stiff layer was set at a depth of 3.7 m (12 ft.).

For the medium-strength structures, the stiff layer was set at 3 m (10 ft.). For the high-strength subgrade structures, the stiff layer was placed at 6 m (20 ft.). (Although the high-strength subgrade was constructed to a controlled depth of 2.8 m (9 ft.) the high-strength subgrade was constructed with the same in situ sands as incorporated in the underlying soil. The use of 6-m (20-ft.) depth to stiff layer is a common practice for backcalculating pavement and subgrade moduli.)

The modulus used for the stiff layer was set to 7000 MPa (1,000,000 psi) with a Poisson's ratio of 0.40.

Evaluation of NDT Response with Force Amplitude

Since laboratory resilient modulus tests indicate the stress dependent nature of subgrade soils, NDTs are often conducted at a force amplitude consistent with expected aircraft loading. This suggests that the NDT response is nonlinear with increasing force, i.e., measured pavement stiffness and backcalculated subgrade modulus would change with increasing force amplitude.

To test this, same location FWD data at four loads and HWD data at three loads were evaluated. The impulse stiffness modulus (ISM) was computed for each load at each test location, where ISM is the ratio of force to center plate response. The backcalculated subgrade modulus (E) was also computed with FAABACKCAL at each force amplitude. The results are summarized in Table 3. As shown, both the ISM and backcalculated subgrade modulus are relatively constant with FWD and HWD force amplitude. This is similar to HWD tests conducted at center slab on instrumented rigid pavements at Denver International Airport (DIA). HWD data files for the DIA instrumented pavements can be found in the DIA database (Lee, et al., 1997). The linear response with load for both flexible and rigid pavements suggest that using NDT force amplitudes at proto-typical aircraft loading is not necessary to evaluate airport pavements. This suggests that airport pavements can be evaluated satisfactorily with lighter load devices, such as the FWD, provided sufficient response is obtained to allow for reliable sensor recordation.

Comparison of ISM Results

Since both stabilized (*FS) and nonstabilized (*FC) pavements were designed to provide equal performance, one would expect the ISM results to be fairly constant for all sections. However, the ISM results for stabilized-base sections are consistently higher than the ISMs for nonstabilized-base sections, even though subgrade moduli (and CBRs) are relatively consistent between sections. This may suggest some inconsistencies in current design methods with the conventional to stabilized-base transformations.

Similarly, the stiffness of low- and medium-strength conventional and stabilized-base sections are approximately equal, suggesting consistency in current design methods over different subgrade strengths. Although this may also be present when extending to the high-strength section, the as-built subgrade strength significantly exceeded the design assumptions, possibly masking the effect.

However, these observations present an admittedly simplistic description of pavement performance and require more study, which is beyond the scope of this paper.

Table 3. Evaluation of NDT response as a function of force amplitude.

Pavement	Equipment	Average Force		Average ISM		Average E	
		(kN)	(lbs)	(kN/mm)	(k/in)	(MPa)	(psi)
Initial Tests After Completion of Construction							
LFC	FWD	39	8,793	114	651	49	7,047
		60	13,395	110	626	51	7,326
		82	18,331	110	631	49	7,160
		114	25,521	113	643	51	7,325
LFS	FWD	40	8,897	175	1,002	46	6,691
		60	13,557	172	982	47	6,832
		83	18,558	172	982	47	6,805
		115	25,882	176	1,003	48	6,899
MFC	FWD	39	8,771	107	609	89	12,915
		59	13,345	104	593	89	12,950
		81	18,252	103	590	89	12,863
		113	25,407	103	586	89	12,853
MFS	FWD	39	8,803	204	1,167	101	14,659
		60	13,466	201	1,150	102	14,740
		82	18,453	198	1,132	101	14,615
		115	25,888	201	1,148	102	14,722
HFC	FWD	39	8,798	146	832	265	38,388
		60	13,435	144	821	263	38,102
		82	18,407	144	823	255	36,932
		114	25,628	145	826	249	36,045
HFS	FWD	39	8,874	273	1,559	275	39,830
		60	13,572	272	1,553	274	39,750
		83	18,568	270	1,545	266	38,584
		115	25,898	273	1,560	264	38,342
Test Pits - Before Opening							
LFS	HWD	55	12,380	292	1,669	69	10,057
		110	24,713	293	1,675	74	10,785
		162	36,488	292	1,671	72	10,486
MFS	HWD	55	12,330	307	1,757	100	14,526
		109	24,597	311	1,776	104	15,122
		162	36,369	312	1,781	102	14,830
HFS	HWD	55	12,408	363	2,076	241	34,932
		111	24,856	362	2,071	239	34,598
		162	36,470	361	2,065	233	33,799
Test Pits - After Opening							
LFS	HWD	50	11,221	234	1,336	74	10,773
		107	24,061	234	1,338	80	11,597
		159	35,783	232	1,326	78	11,320
MFS	HWD	50	11,178	251	1,432	97	14,116
		107	24,060	252	1,441	103	14,867
		159	35,845	253	1,446	101	14,632
HFS	HWD	50	11,213	323	1,844	225	32,703
		107	24,131	320	1,827	221	32,082
		160	35,944	314	1,796	215	31,246

CBR-E Correlation

The LEDFAA program contained in the FAA Advisory Circular 150/5320-16 (FAA, 1995) uses the relationship E(psi) = 1500 x CBR for computing the elastic modulus of subgrade soils for layered elastic computations. This relationship was also used by Barker (Barker, et al., 1975) to compute subgrade vertical strains for full-scale test pavements when developing the mechanistic flexible pavement failure criteria used in LEDFAA. The relationship, originally developed by Huekelom and Klomp (Huekelom, et al., 1962), suggests that the subgrade CBR is directly related to the elastic (resilient) modulus.

Since the E = 1500 x CBR relationship is widely used and is embedded in the FAA's mechanistic design procedure, the NDT and CBR data obtained at the NAPTF were used to verify the correlations or to suggest modifications. Further, since NDT is a fairly common method for evaluating airport pavements, the backcalculated modulus is often transformed to a subgrade CBR using the Huekelom and Klomp relationship for conventional pavement evaluation in accordance with the FAA Advisory Circular 150/5320-6D (FAA, July 1995).

For the regression analyses, the E-CBR data for each subgrade section were averaged and paired as indicated in Table 4. The CBR results at the top of the subgrade from Tables 1 and 2 were used as the representative subgrade CBR for each section and paired with the average backcalculated subgrade modulus from Table 3.

Table 4. E-CBR correlation.

Subgrade	**Average E**		**CBR**
	(MPa)	**(psi)**	**(%)**
Initial FWD Testing			
Low	48	7,000	3.3
Medium	95	13,790	8.5
High	264	38,250	29.5
Test Pit FWD Testing			
Low	75	10,836	5.3
Medium	101	14,682	7.0
High	229	33,267	34.0

The results of linear and nonlinear regressions yielded the following regression equations:

$$E = 1171\ CBR,\ R^2 = 0.83$$

$$E = 3363\ CBR^{0.6863},\ R^2 = 0.97$$

The linear and nonlinear regressions are plotted in Figures 2 and 3, respectively, with the E = 1500 x CBR relationship superimposed on each figure.

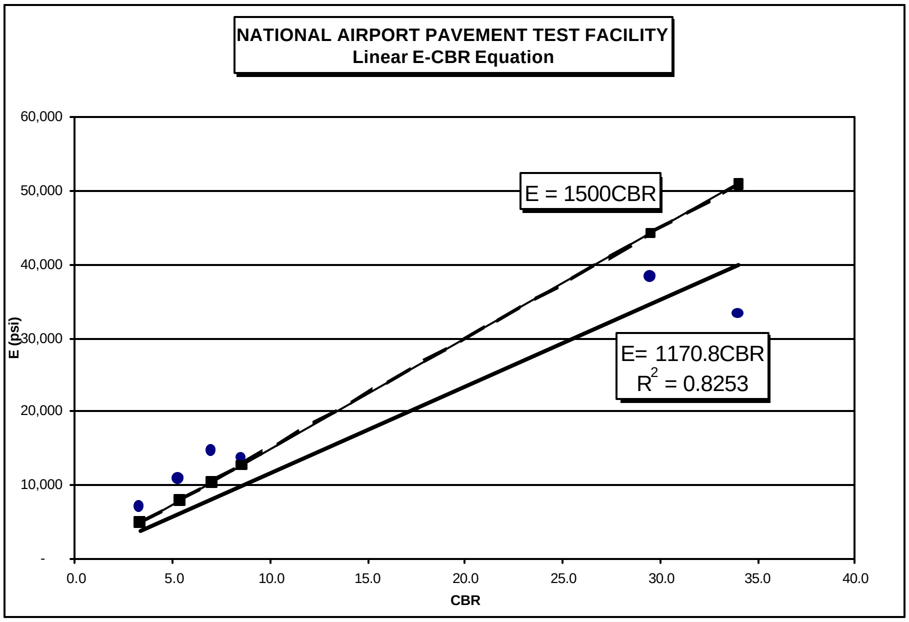

Figure 2. Linear E-CBR equation.

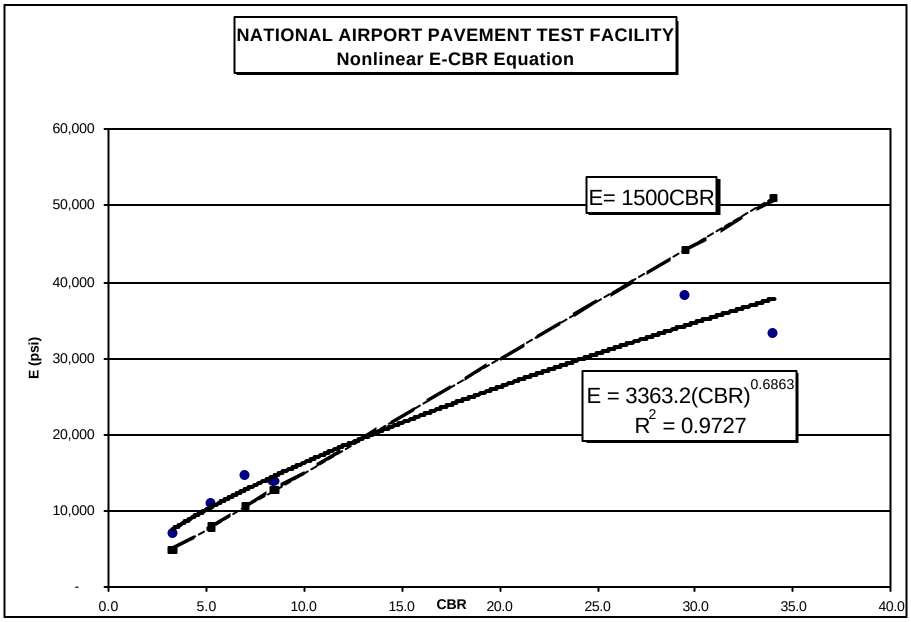

Figure 3. Nonlinear E-CBR equation.

Although the data used for the regressions are sparse, at n=6, the correlation coefficients (R^2) indicate that the relationships are significant, with the nonlinear equation providing a better fit to the data. Green and Hall (Green, et al., (1975) also suggested a nonlinear relationship of E(psi) = 5409 x $CBR^{0.711}$. However, this relationship provided a poor fit to the NAPTF data.

Comparing the regression equations derived from the NAPTF data to the commonly used E = 1500 x CBR relationship and recognizing that the NAPTF data are limited, it appears that the use of E(psi) = 1500 x CBR is reasonable when applied to the subgrade modulus backcalculated from FWD and HWD measurements. The nonlinear relationship is also fairly consistent with the E = 1500 x CBR relationship over the range of CBR's typically encountered in the field, i.e., $3 < CBR < 20$. Since the flexible pavement failure criteria embedded in the LEDFAA program (FAA, 1995) was derived using this relationship, this suggests that the backcalculated subgrade modulus from NDT can be used in the LEDFAA program. The NAPTF data also suggest that the backcalculated subgrade modulus can be used to estimate the in situ CBR for conventional analyses using the E(psi) = 1500 x CBR relationship.

As additional E-CBR data are obtained during continued testing at the NAPTF, the correlation equations can be revisited.

Laboratory Resilient Modulus

The materials database also contains resilient modulus data performed in accordance with SHRP P46 for samples of low- and medium-strength subgrade soils. For the low-strength soils, the modulus generally varies from approximately 14 to 52 MPa (2,600 to 7,500 psi), depending on confining pressure and deviator stress. Likewise, for the medium-strength soils, the modulus generally varied from 34 to 86 MPa (5,000 to 12,500 psi). The subgrade moduli backcalculated from the NDT data are generally consistent with the laboratory resilient modulus obtained at 41 kPa (6 psi) confining stress and 14 kPa (2 psi) deviator stress.

Effect of Stiff Layer

As discussed, a stiff layer was incorporated into the backcalculations based on the depth of the in situ native soils below the surface. The use and importance of incorporating an underlying stiff layer is well documented in the literature.

Initially, the FAA backcalculation program was used to compute the modulus of the underlying in situ layer to obtain a best fit. Sensitivity analysis found that the computed subgrade modulus was relatively insensitive to the modulus of the stiff layer at moduli in excess of 3500 MPa (500,000 psi).

As the modulus of the stiff layer decreased from 3500 MPa (500,000 psi) down to 140 MPa (20,000 psi), the computed value of the subgrade modulus increased. If the stiff layer was shifted down to 6 m (20 ft.), the low- and medium-strength moduli increased by approximately 100% and 150%, respectively, when compared to placement of the stiff layer according to the as-built conditions. This underscores the need to identify the location of underlying stiff layers during routine NDT pavement evaluations.

Conclusions

The analysis of the NDT data obtained at the FAA's NAPTF yielded several interesting findings. These include:

- The FAA's backcalculation software, incorporating the LEAF layered elastic program, yielded results consistent with WESDEF. The FAABACKCAL program can be downloaded as an executable or source code from the FAA Airport Technology Branch web site: www.airporttech.tc.faa.gov.
- Pavement stiffnesses (ISM) and backcalculated subgrade moduli are independent of FWD and HWD force amplitudes. This was also found to be true for the mid-slab rigid pavement HWD data collected at the DIA instrumented pavement. This suggests that heavy load NDT devices such as the HWD may not be necessary to reliably evaluate airport pavements and lighter load devices, such as the FWD, can provide equally reliable data.
- Based on a comparison of pavement stiffnesses (ISM) for conventional and stabilized-base pavements constructed on the same subgrade, there may be some inconsistencies in the conventional to stabilized-base transformations used in the FAA design method. However, the consistent stiffnesses of like pavements on subgrades of different strengths suggest consistency in current design methods over a range of subgrade strengths. These observations do, however, represent a simplistic representation of pavement performance and require a level of study that was beyond the scope of this paper.
- The NDT and CBR data acquired at the NAPTF suggest that the commonly used E(psi) = 1500 x CBR relationship is reasonable when applied to the subgrade modulus (E) backcalculated from FWD and HWD measurements within the range $3 < CBR < 20$. Since the flexible pavement failure criteria embedded in the FAA's LEDFAA (FAA, 1995) program were derived using this relationship (Barker, et al., 1975), this suggests that the backcalculated subgrade modulus can be used in LEDFAA. Further, based on the NAPTF data (albeit limited), the E = 1500 x CBR relationship can be used within the range $3 < CBR < 20$ to estimate the in situ CBR from backcalculated subgrade modulus for use in conventional (FAA, July 1995) pavement design analyses.
- The backcalculated subgrade moduli for low- and medium-strength subgrades compares to resilient modulus data at 41 kPa (6 psi) confining stress and 14 kPa (2 psi) deviator stress. The comparisons were poor for other stresses.

The data used for the analyses presented in this paper are contained in the FAA's materials and NDT databases which can be obtained from the FAA Airport Technology Branch web site: www.airporttech.tc.faa.gov. As the research efforts continue, the databases will be updated.

Acknowledgements/Disclaimer

The work described in this paper was supported by the FAA Airport Technology Research and Development Branch, Manager, Dr. Satish K. Agrawal. The contents of the paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the FAA. The paper does not constitute a standard, specification, or regulation.

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