Pavement Evaluation and Overlay Design: A Method That Combines Layered-Elastic Theory and Vibratory Nondestructive Testing

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A procedure has been developed for the determination of the load-carrying capacity and required overlay thickness of airport pavements. The procedure combines a layered-elastic theoretical approach and vibratory nondestructive testing to determine the value of the Young's modulus of the subgrade. A computer program SUBE is used to determine the value of the Young's modulus of the subgrade from the measured dynamic response of a pavement. A computer program PAVEVAL is used to calculate the load-carrying capacity and required overlay thickness in terms of the structure of the pavement and subgrade and in terms of limiting strain and stress conditions. The procedure was evaluated by calculating the load-carrying capacity and overlay thicknesses for single-wheel and multiple-wheel loadings on rigid and flexible pavements.

The increasing cost of pavement construction and rehabilitation makes it essential to have a fast and reliable method of accurately determining the load-carrying capacity of a pavement and of predicting the overlay thickness that will be required to upgrade it. A method for the rapid evaluation of airport pavements has been developed at the U.S. Army Engineer Waterways Experiment Station (WES) for the Federal Aviation Administration. This method of pavement evaluation and overlay design is based on vibratory nondestructive testing combined with a layered-elastic theoretical formalism (1-6).

This method of pavement evaluation and overlay design consists of the determination of the Young's modulus of the subgrade from the dynamic response of the pavement as measured by vibratory nondestructive tests, followed by the use of layered-elastic theory and the predicted value of the Young's modulus of the subgrade for the calculatation of the allowable load-carrying capacity and the required overlay thickness of the pavement.

The method of layered-elastic theory and vibratory nondestructive testing is compared with the conventional method for evaluating asphalt concrete (AC) pavements that uses the California bearing ratio (CBR) and with the Westergaard method for evaluating portland cement concrete (PCC) pavements (7). It is also compared with the method of pavement evaluation that uses a correlation between the strength of a pavement and the dynamic stiffness modulus (DSM) that can be obtained from vibratory nondestructive testing (1).

The CBR and the Westergaard methods require destructive tests that measure the CBR and the coefficient of subgrade reaction, respectively. To circumvent these destructive tests, a vibratory, nondestructive testing method for evaluating AC and PCC pavements was developed at WES that directly correlates the load-carrying capacity and the required overlay thickness to a mechanical impedance that is measured at the pavement surface (the DSM).

The DSM is calculated from data that are obtained by using a hydraulic vibrator developed at WES that can generate dynamic loads up to 71 kN [16 000 lbf(16 kips)]a constant 71-kN static load and a constant frequency of 15 Hz (4). The data obtained consist of curves of the dynamic load versus the deflection that is measured at the pavement surface. These dynamic-load-deflection curves are generally nonlinear; the DSM is the slope of the curve at a dynamic load of about 62-67 kN [14 000 to 15 000 lbf (14-15 kips)]. The measured DSM is corrected to that at a common pavement temperature of 21°C (70°F), and the corrected value of the DSM is correlated with the load-carrying capacity and required overlay thickness of the pavement (1, 6). The DSM method is empirical and does not include the effects of the layered elastic structure of the pavement or of the interface conditions between the pavement layers.

This method of directly correlating pavement performance with vibratory, nondestructive testing data can be improved by combining the layered-elastic theory of pavement behavior with the pavement-impedance values measured by the vibratory testing. In this way, the effect of the pavement structure can be considered. The layered-elastic model of pavement behavior requires that the Young's moduli and Poisson's ratios of the subgrade and pavement layers be known. The elastic moduli of the pavement layers were estimated by various means; the Young's modulus of the subgrade was obtained by vibratory nondestructive tests.

IMPEDANCE METHOD FOR DETERMINATION OF YOUNG'S MODULUS OF SUBGRADE

Measurement of Pavement Impedance

The WES 71-kN vibrator applies to the pavement surface a static load of 71 kN and a dynamic load of up to 67 kN at a frequency of 5-100 Hz. Both loads are applied to the pavement surface through a circular 46-cm (18-in) diameter baseplate. The vibrator can perform two types of nondestructive impedance tests:

1. Tests that determine the dynamic deflection of the pavement surface as a function of the applied load at a fixed frequency (i.e., tests that produce dynamic-load-deflection curves) and
2. Tests that determine the dynamic deflection as a function of the frequency at a fixed dynamic load (i.e., tests that produce frequency-response-spectrum curves).

Only method 1 above is used in this paper to determine the Young's modulus of the subgrade. In general, these dynamic-load-deflection curves are nonlinear and a nonlinear dynamic theory is required to extract the value of the subgrade Young's modulus from them by removing the extraneous effects of the static and dynamic loads developed by the vibrator on the predicted values of the subgrade Young's modulus (3, 4). The computer program SUBE was developed from the nonlinear theory of pavement response to dynamic loads and used to determine the Young's modulus of the subgrade from the measured dynamic-load-deflection curves.

A typical dynamic-load-deflection curve measured at 15 Hz is shown in Figure 1.

Nonlinear Dynamic Theory of Pavement Response

In the nonlinear dynamic theory of pavement response that was developed to describe the dynamic-load-deflection curves and to predict the value of the Young's modulus of the subgrade, the dynamic response of the pavement surface to forced vibrations is modeled as a nonlinear harmonic oscillator whose equation of motion is

$$m\ddot{x} + C\dot{x} + k_{00}x + bx^3 + ex^5 = F_V = F_S + F_D \quad (1)$$

where

- m = effective mass of pavement,
- $\ddot{x}$ = acceleration of pavement surface,
- C = damping constant,
- $\dot{x}$ = velocity of pavement surface,
- k_{00} = linear spring constant,
- x = total displacement of pavement surface,
- b = third-order nonlinear coefficient,
- e = fifth-order nonlinear coefficient,
- F_V = total force applied by vibrator,
- F_S = static force applied by vibrator, and
- F_D = dynamic force applied by vibrator.

From Equation 1, the static force is

$$F_S = k_{00}x_e + bx_e^3 + ex_e^5 \quad (2)$$

where x_e = static elastic displacement of the pavement surface.

The solution of the equation of motion of the pavement surface is

$$x = x_e + \xi \quad (3)$$

where ξ = dynamic displacement of the pavement surface. Thus, the solution of Equation 1 is given by considering a sum of harmonic terms, $\cos \omega t$, $\cos 3\omega t$, and $\cos 5\omega t$ to obtain the equivalent linear spring constant:

$$k = k_0 + (3/4)b\theta\xi^2 + (5/8)e\eta\xi^4 \quad (4)$$

where

$$k_0 = k_{00} + 3b\epsilon_2 x_e^2 + 5e\epsilon_4 x_e^4 \quad (5)$$

and

- k = dynamic spring constant,
- k_0 = static elastic spring constant, and
- θ, η, ϵ_2, and ϵ_4 = dimensionless parameters.

When these substitutions are made, the solution to the equation of motion is

$$\xi = (F_D/S_0)(1 + \alpha_1 \psi + \alpha_2 \psi^2) \quad (6)$$

$$S = S_0(1 + \beta_1 \psi + \beta_2 \psi^2) \quad (7)$$

$$DSM = S_0(1 + \delta_1 \psi + \delta_2 \psi^2) \quad (8)$$

where

- S_0 = impedance at zero dynamic load,
- α_1 and α_2 = frequency-dependent coefficients related to the nonlinear elastic parameters b and e,
- ψ = F_D^2/S_0^4,
- S = secant dynamic modulus (impedance),
- DSM = tangent dynamic modulus (impedance),

and the β_j and δ_j coefficients are given by

$$\beta_1 = -3\alpha_1 \quad (9)$$

$$\beta_2 = \alpha_1^2 - \alpha_2 \quad (10)$$

$$\delta_1 = -3\alpha_1 \quad (11)$$

and

$$\delta_2 = 9\alpha_1^2 - 5\alpha_2 \quad (12)$$

The terms $\alpha_1\psi$ and $\alpha_2\psi^2$ in Equations 6-8 describe the departure from linear of the dynamic-load-deflection curve. The quantities α_1 and α_2 are measured directly from these curves.

The dynamic quantities S_0, α_1, and α_2 can be related to the static elastic parameters k_{00}, b, and e, which in turn are related to the Young's moduli of the pavement layers and the subgrade. Therefore, the shape of the dynamic-load-deflection curve depends on the layered-elastic structure of the pavement. For example,

$$\alpha_1 = -(3/4)b\theta(k_0 - m\omega^2) \quad (13)$$

The values of k_{00}, b, and e can be expressed in terms of the elastic moduli of the pavement layers and the subgrade and in terms of the finite depth of influence of the stress and strain field that is produced in the pavement and the subgrade by the static load of the vibrator.

The general expressions for k_{00}, b, and e in terms of the elastic structure of a pavement are rather complex but, for the case of a homogeneous half space, they simplify as follows:

$$l = l_0 + l_2 x_e^2 + l_4 x_e^4 \quad (14)$$

$$k_{00} = 2\pi a^2 \Psi(1 - \nu_S)G_S/l_0(1 - 2\nu_S) \quad (15)$$

$$b = -4\pi a^2 \Psi l_2(1 - \nu_S)G_S/l_0^2(1 - 2\nu_S) \quad (16)$$

and

$$e = 6\pi a^2 \Psi \delta(1 - \nu_S)G_S/l_0(1 - 2\nu_S) \quad (17)$$

where

$$\delta = (l_2/l_0)^2 - l_4/l_0 \quad (18)$$

- l = finite depth of influence of the static stress and strain field on the pavement and subgrade,
- l_0, l_2, and l_4 = coefficients of series expansion of finite depth of influence,
- a = radius of vibrator baseplate,
- ψ = volume factor for the frustum of the cone of stress and strain in the pavement,
- ν_S = Poisson's ratio of subgrade, and
- G_S = shear modulus of subgrade.

[More general expressions for a layered system are given by Weiss (3).] Therefore, it is possible to relate the

Figure 1. Typical dynamic-load-deflection curve for AC pavement.

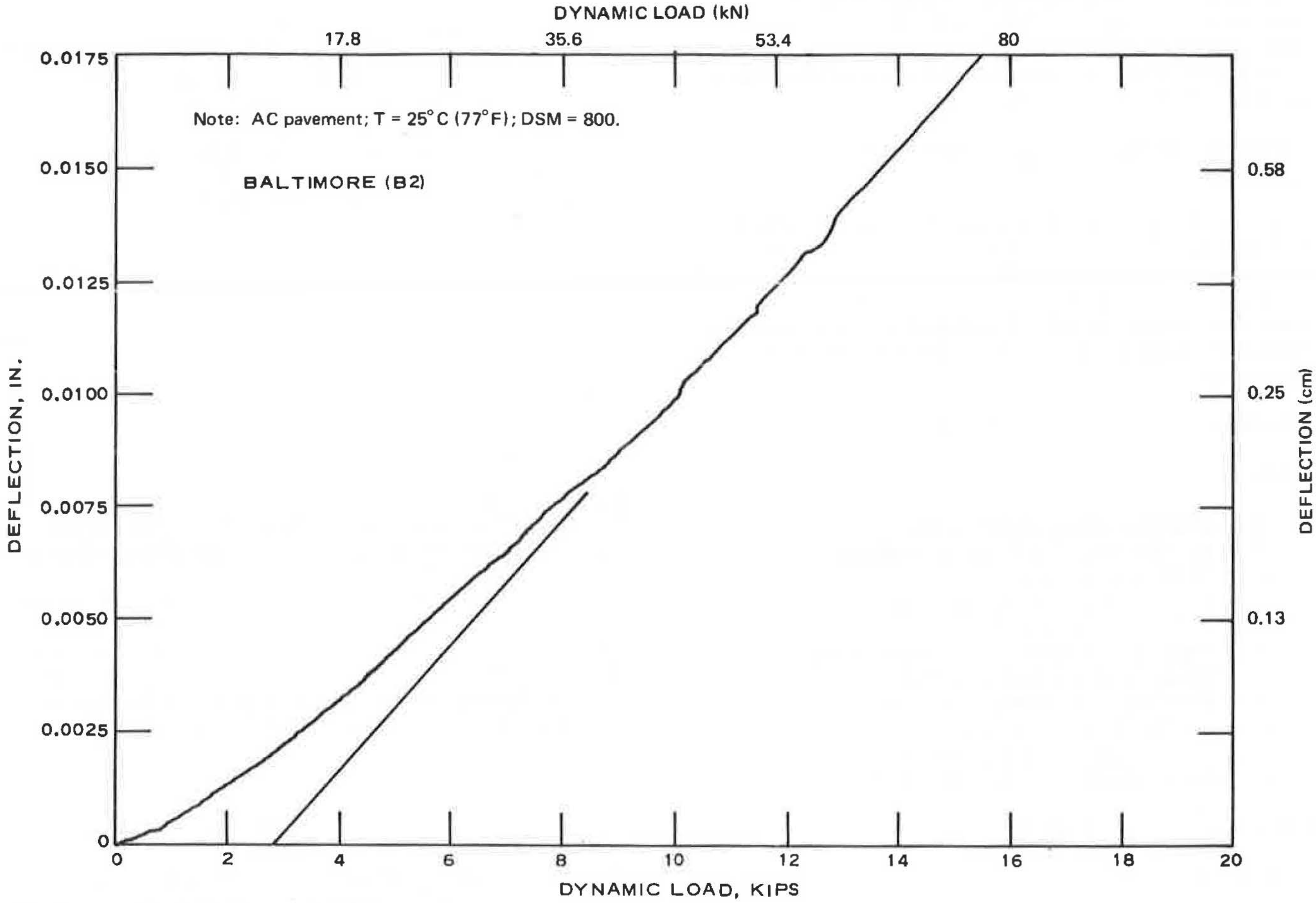
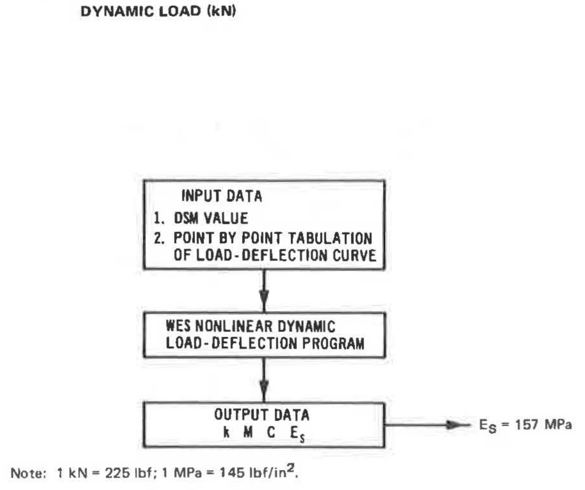


Figure 2. Determination of modulus of subgrade from a measured load-deflection curve.



Note: 1 kN = 225 lbf; 1 MPa = 145 lbf/in².

elastic structure of a pavement and its subgrade to a dynamic-load-deflection curve as described by the parameters S_0, α_1, and α_2.

For a specific choice of the elastic moduli of the pavement layers (and the choice $\nu = 0.35$ for the subgrade), the shape of the theoretically predicted dynamic-load-deflection curve depends only on the value of the Young's modulus of the subgrade. This value is obtained by requiring that the theoretically predicted dynamic-load-deflection curve agree with the measured dynamic-load-deflection curve.

Dynamic Pavement-Response Computer Program

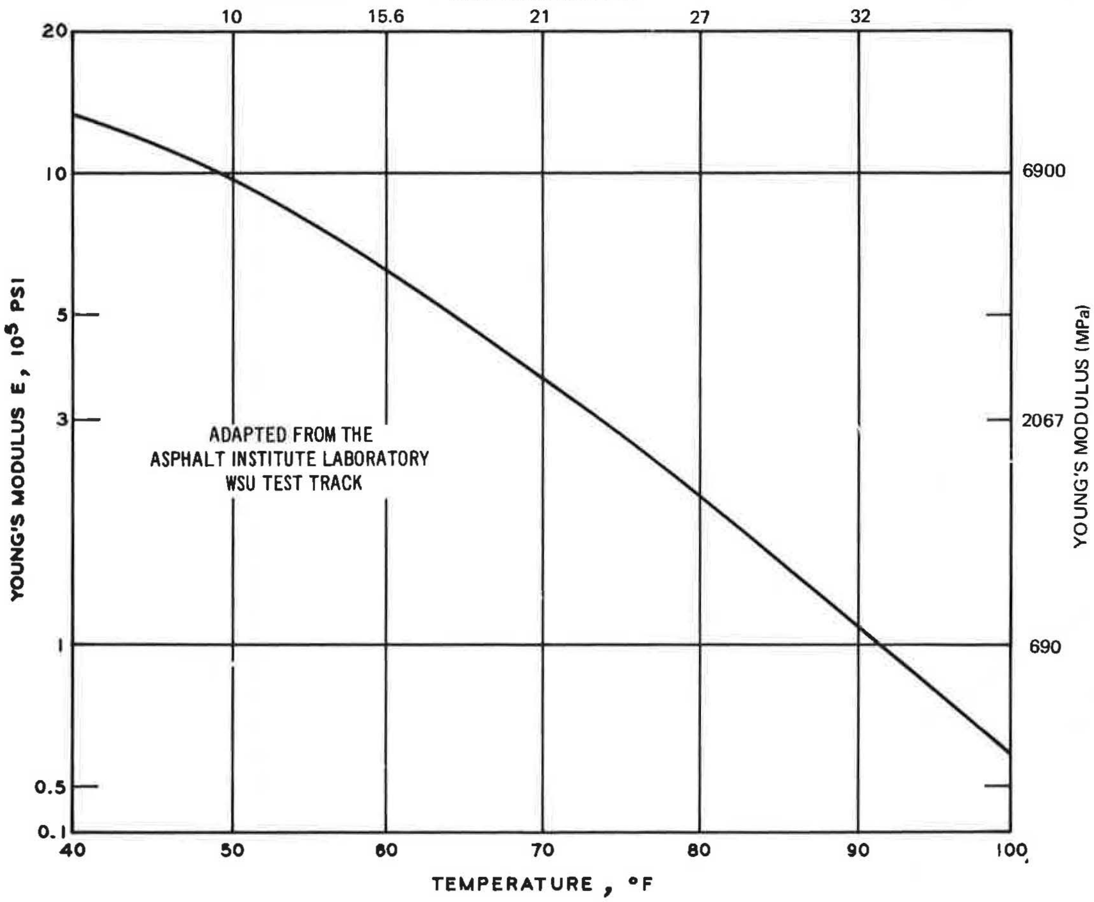
The computer program SUBE is used to calculate the value of the Young's modulus of the subgrade from input data taken from the measured dynamic-load-deflection curves (4). The pavement input parameters for the program include the Young's modulus, Poisson's ratio, and thickness of each pavement layer and the Poisson's ratio of the subgrade. The input that is taken from the vibratory, nondestructive testing data is the DSM value and a point-by-point description of the measured dynamic-load-deflection curve. The program iterates the value of the Young's modulus of the subgrade and determines the value of it that makes the theoretically predicted DSM value agree with the measured DSM value so that the theoretically predicted dynamic-load-deflection curve will agree with the measured dynamic-load-deflection curve. The procedure is outlined in Figure 2 for the pavement described below at 25°C

Table 1. Young's moduli and Poisson's ratios of base and subbase materials.

Material	Description	Assigned Value of Young's Modulus (MPa)	Assigned Value of Poisson's Ratio
Crushed limestone	Crushed limestone	551	0.35
GW	Well-graded gravel	413	0.35
GW-GM	GW and silty gravel	345	0.35
GP	Poorly graded gravel	276	0.35
GP-GC	GP and clayey gravel	241	0.35
SP-SM	Poorly graded sand and silty sand	207	0.35
Black base	Mineral aggregate and bituminous material	Temperature dependent	0.30

Note: 1 MPa = 145 lbf/in².

Figure 3. Assumed temperature dependence of Young's modulus of AC pavements and AC base materials.



(77°F) (1 MPa = 145 lbf/in^2 and 1 cm = 0.4 in).

Pavement Layer	E (MPa)	ν	H (cm)
AC	1380	0.30	12.7
Black base	1380	0.35	17.8
GW-GM	207	0.35	22.3
SM-SC	E_s	0.35	

The Poisson's ratios of the wearing surfaces, base courses, and subbase courses were chosen as $\nu = 0.2$ for PCC pavements, $\nu = 0.3$ for AC pavements and base materials, and $\nu = 0.35$ for all other base and subbase materials. The Poisson's ratio for all subgrade soils was taken to be $\nu = 0.35$. Reasonable estimates of the values of the Young's moduli of base and subbase materials are given in Table 1. When the CBRs of the base and subbase materials are known, the Young's modulus values can be estimated by using the equation E = 1500 CBR (2, 8).

The Young's modulus of the PCC wearing surface of a rigid pavement was taken as 27 600 MPa (4 000 000 lbf/in^2). The temperature-dependent Young's modulus for AC pavements and base materials was obtained from Figure 3 for the pavement surface temperature at the time of the vibratory testing. The value of the temperature-dependent Young's modulus is entered into the SUBE computer program to determine the Young's modulus of the subgrade.

Laboratory Resilient-Modulus Tests

The values of the Young's modulus of the subgrade predicted from the vibratory nondestructive field tests by using the SUBE computer program were correlated with the values of the Young's modulus of the subgrade determined by laboratory resilient-modulus (M_R) tests. The laboratory resilient modulus is expressed in terms of the applied dynamic deviator stress and the static confining pressure (9, 10). Some examples of resilient-modulus test data (obtained from undisturbed subgrade soil samples taken at three selected airport pavement sites) are shown in Figures 4-6.

The results of the laboratory resilient-modulus test can also be described in terms of a nonlinear harmonic oscillator. An analysis (similar to that used to describe the dynamic-load-deflection curves obtained in the field) of the laboratory test data gave the following theoretical expressions for the resilient modulus (4):

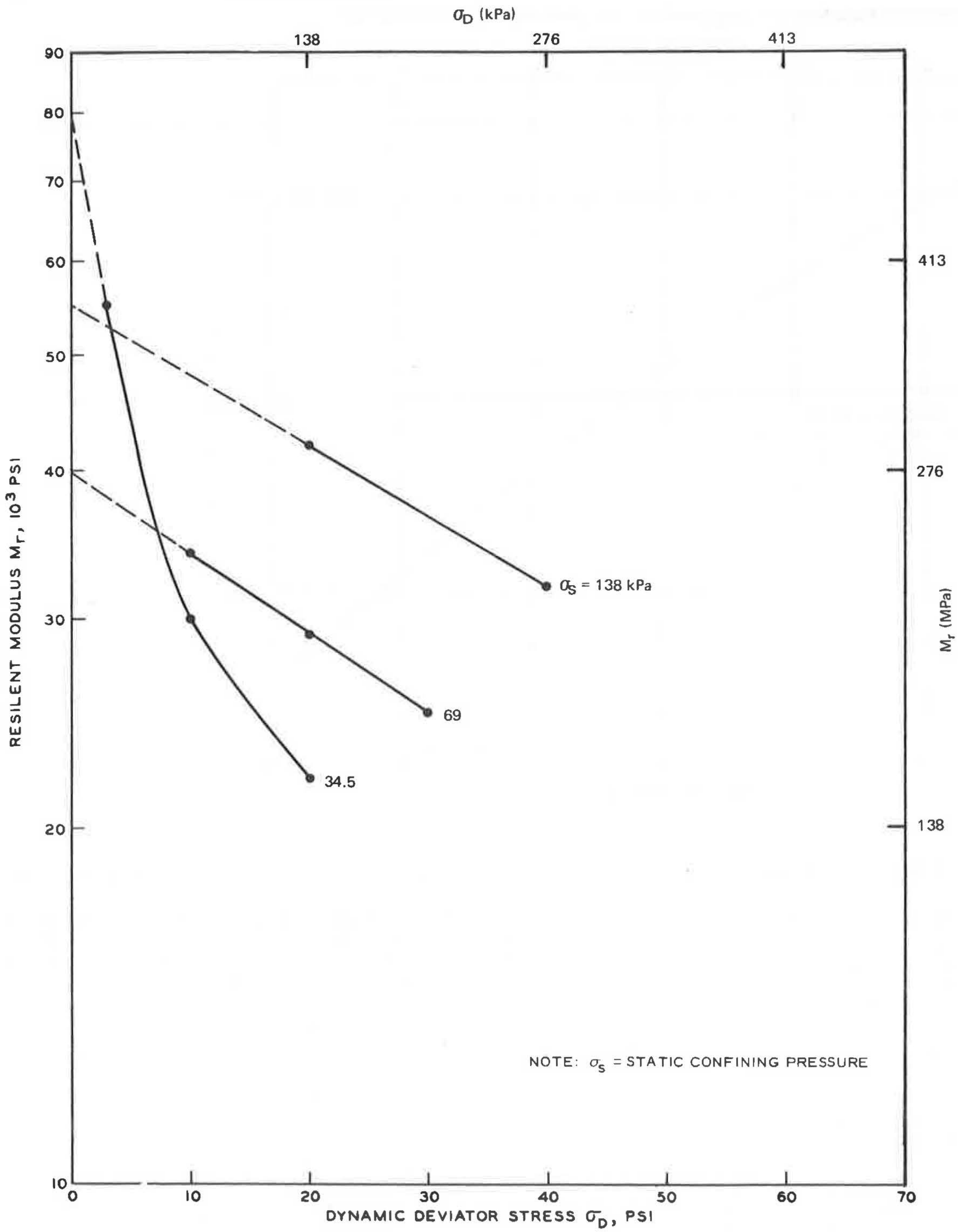
$$M_{rs} = M_{r0}\,[1 + \beta_1'\,\psi' + \beta_2'(\psi')^2] \tag{19}$$

$$M_{rt} = M_{r0}\,[1 + \delta_1'\,\psi' + \delta_2'(\psi')^2] \tag{20}$$

where

M_{rs} = secant resilient modulus,

Figure 4. Laboratory resilient modulus: Albuquerque site 17.

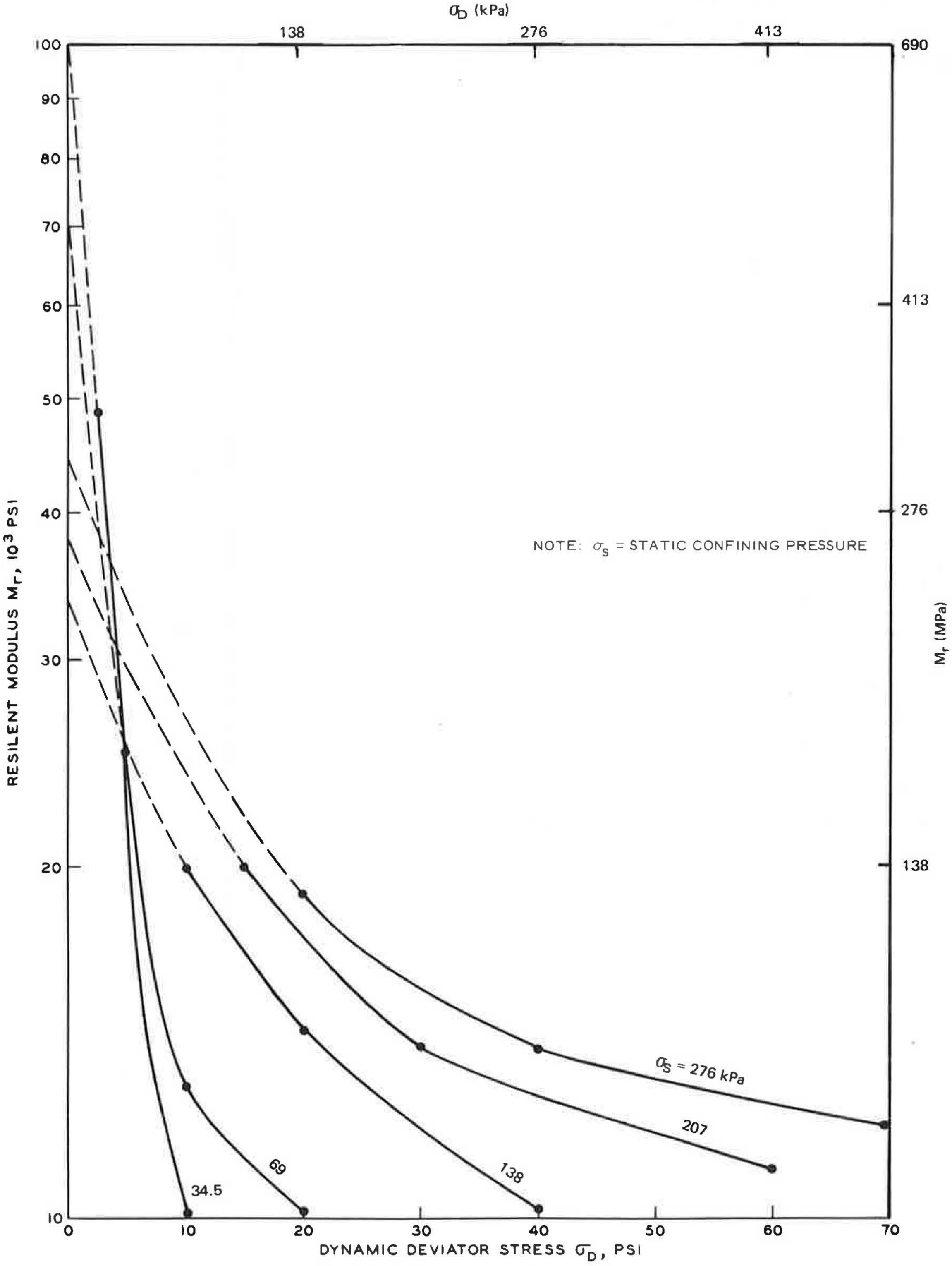


M_{rt} = tangent resilient modulus,
M_{r0} = resilient modulus at zero dynamic deviator stress,
ψ' = $A^2\sigma_D^2/S_0'^4$,
A = area of circular base of cylindrical soil specimen,
σ_D = dynamic deviator stress, and
S_0', β_j', and δ_j' = coefficients that depend on the value of the static confining pressure.

The static confining pressure can be described in terms of the static displacement of the cylindrical soil sample as follows:

$$F_S = \sigma_S A = k_{00}' x_e + b'(x_e')^3 + e'(x_e')^5 \quad (21)$$

Figure 5. Laboratory resilient modulus: Rockland site 1.

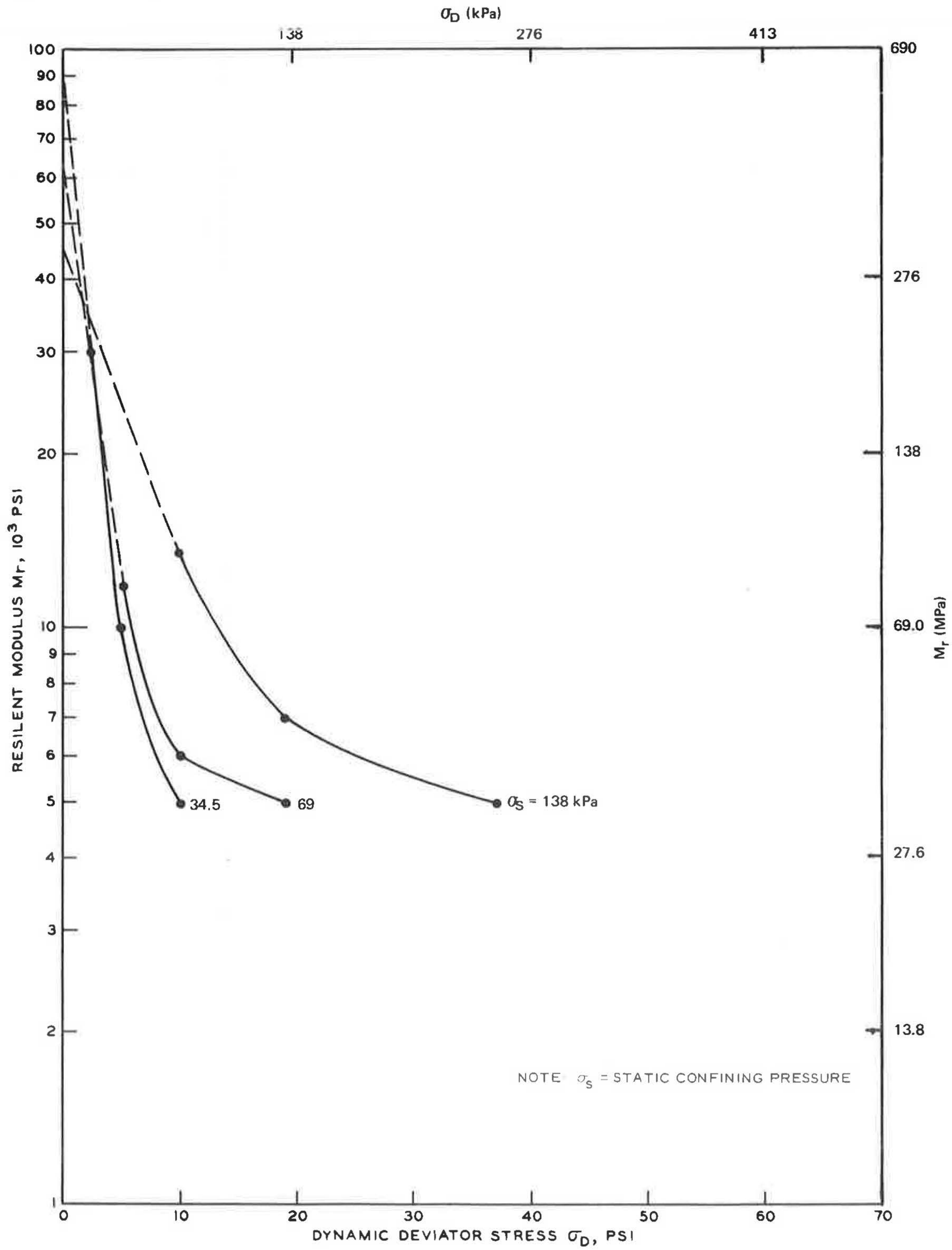


where

σ_s = static confining pressure,
k'_{00} = linear elastic spring constant,
b' = third-order nonlinear elastic coefficient of soil sample,
e' = fifth-order nonlinear elastic coefficient of soil sample, and
x'_e = axial static elastic displacement of soil sample.

The coefficients k'_{00}, b', and e' are related to the coefficients S'_0, β'_1, and β'_2 that appear in the expression for the resilient modulus given by Equation 19 (4). Therefore, the measurement of the resilient modulus allows the determination of the static elastic coefficients k'_{00}, b', and e'.

Figure 6. Laboratory resilient modulus: Rockland site 7.



The value of the Young's modulus of the subgrade depends on the static confining pressure and has been found (11) to be

$$E = L\sigma_S/x'_e = E'_0 + E'_2(x'_e)^2 + E'_4(x'_e)^4 \qquad (22)$$

where

$$E'_0 = Lk'_{00}/A \qquad (23)$$

$$E'_2 = Lb'/A \qquad (24)$$

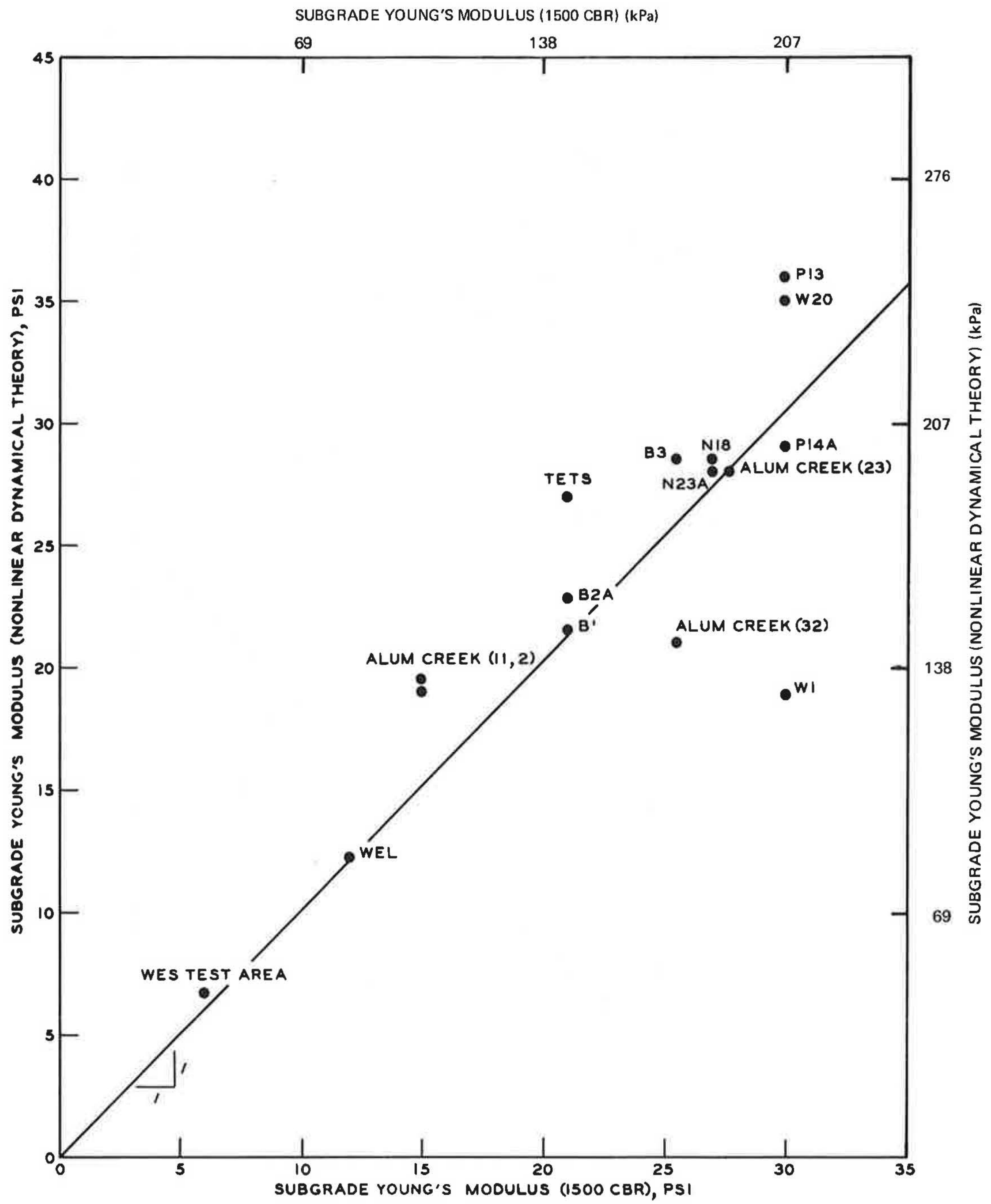
$$E'_4 = Le'/A \qquad (25)$$

and L = length of cylindrical soil sample. (This procedure for determining the Young's modulus of the subgrade from the measured resilient-modulus test data is still under study; only preliminary numerical results are thus far available for comparison with the results obtained from field test data.)

Numerical Values of Predicted Young's Modulus of Subgrade

Laboratory soil-gradation tests were done on samples taken from the base, subbase, and subgrade at the three airport pavement sites investigated. Field measurements of the thicknesses and CBRs were also made on the base, subbase, and subgrade materials (11). The mean pave-

Figure 7. Comparison of values of Young's moduli of subgrades: computer program SUBE versus Shell formula—various airport sites.



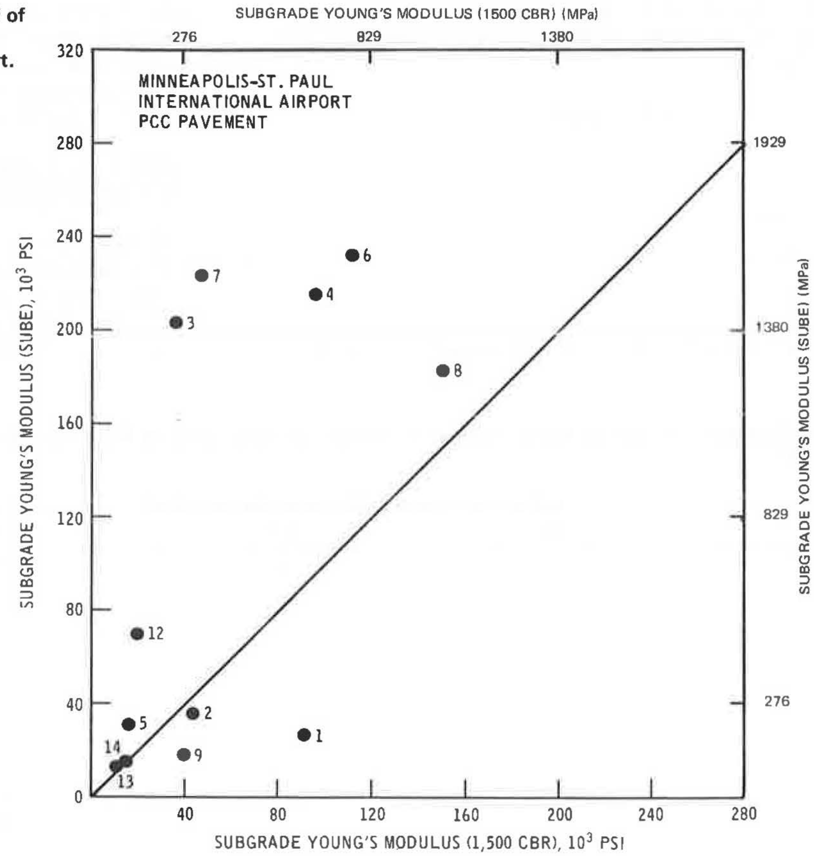


Figure 8. Comparison of values of Young's moduli of subgrades: computer program SUBE versus Shell formula—Minneapolis-St. Paul International Airport.

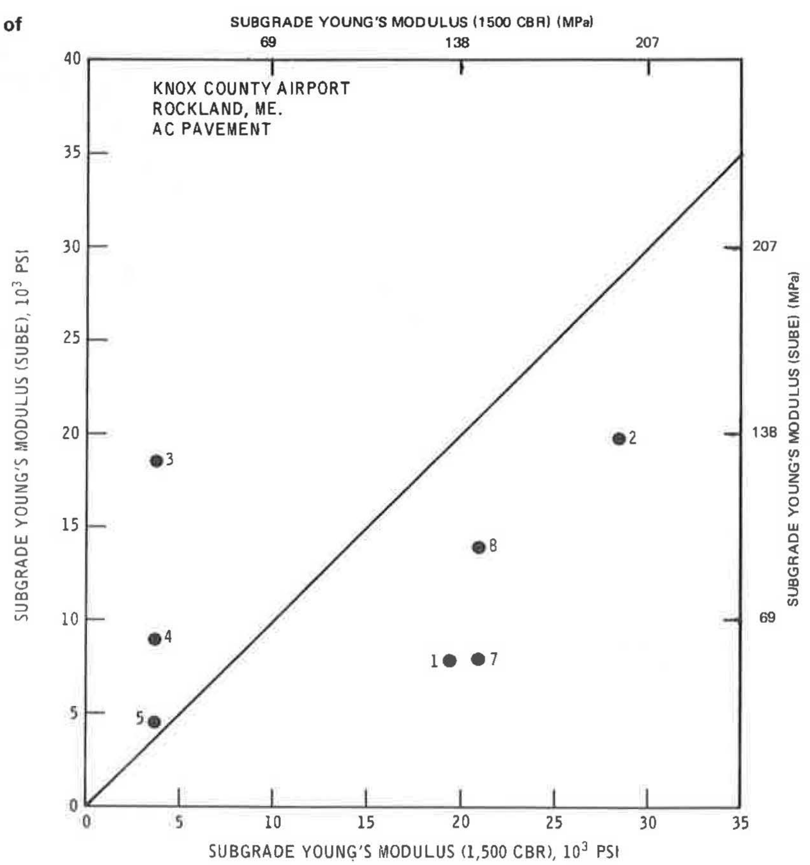
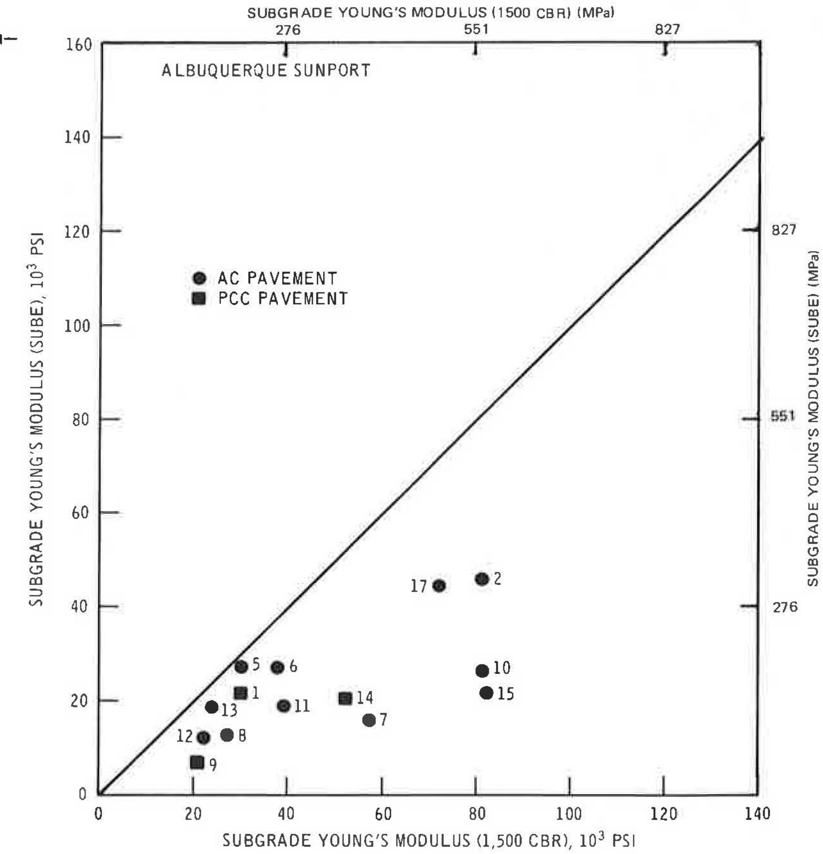


Figure 9. Comparison of values of Young's moduli of subgrades: computer program SUBE versus Shell formula—Knox County Airport, Rockland, Maine.

Figure 10. Comparison of values of Young's moduli of subgrades: computer program SUBE versus Shell formula—Albuquerque, New Mexico, Sunport.



ment temperatures of the AC wearing surface were measured at the time the vibratory nondestructive tests were conducted. From these data, the elastic constants of the pavement layers could be estimated.

A simple relationship between the Young's modulus of the subgrade and the CBR has been derived by wave propagation techniques; this is given by the Shell formula—E_s = 1500 CBR, where E_s = Young's modulus of subgrade (8). The nonlinear dynamic theory of pavement response and the associated computer program SUBE were developed to predict values of the Young's modulus of the subgrade that are in reasonable agreement with the predictions of the Shell formula (4).

Figures 7-10 show comparisons of the values of the Young's moduli of the subgrades predicted by using the nonlinear dynamic-response theory and the computer program SUBE and the values predicted by using the Shell formula. Figures 11 and 12 show comparisons between the values of the Young's moduli of the subgrades determined from the laboratory resilient-modulus tests and predicted by the SUBE and 1500-CBR methods, respectively.

LOAD-CARRYING CAPACITY AND REQUIRED OVERLAY THICKNESS OF PAVEMENTS

PAVEVAL Computer Program

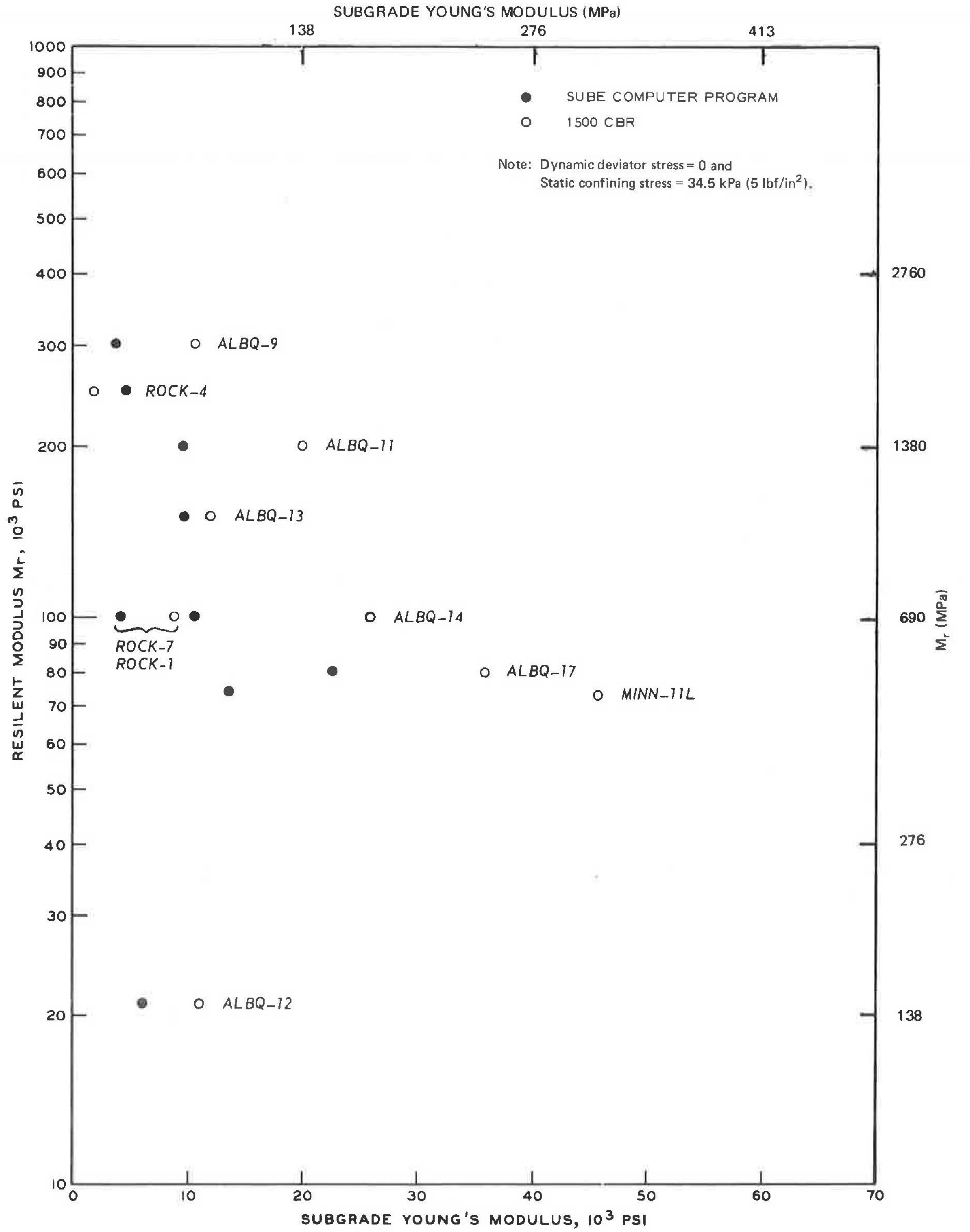
In the context of layered-elastic theory, a pavement is represented as a stack of elastic layers, the subgrade being of infinite extent. This layered-elastic model of a pavement structure can be used to calculate the elastic stress and strain at any point in the pavement or subgrade. Each pavement layer is characterized by a Poisson's ratio (ν), a Young's modulus (E), and a layer thickness (h). The Shell BISAR computer program, which is based on layered-elastic theory, relates the stress and strain in each pavement layer to the static load applied to the surface of a pavement.

The condition of failure in an AC pavement can be described by a limiting elastic (resilient) vertical strain in the top of the subgrade and a limiting tensile strain at the bottom of the AC pavement layer, and the condition of failure in a rigid pavement can be described by a limiting tensile stress at the bottom of the PCC layer (12, 13). For a given load at the pavement surface, the values of the stress and strain in the pavement and subgrade depend on the Young's moduli and the Poisson's ratios of the subgrade and each pavement layer. Therefore, if the elastic moduli of the pavement layers are known, it is the Young's modulus of the subgrade that is the unknown parameter that determines the stress and strain in the pavement and subgrade; thus, this is the parameter that must be determined by vibratory nondestructive testing and the computer program SUBE. The procedure is outlined in Figure 13.

The basic BISAR computer program was modified to include a procedure for the iteration of the surface load and the overlay thickness until, for AC pavements, the vertical strain at the top of the subgrade equals the limiting value of the vertical strain or the tensile strain at the bottom of the AC layer equals the limiting value of the tensile strain or, for PCC pavements, the tensile stress at the bottom of the PCC layer equals the limiting value of tensile stress. The resulting computer program is called PAVEVAL and was used to calculate the load-carrying capacity and required overlay thickness of a pavement (14). The aircraft characteristics required for the PAVEVAL computer program include tire contact area, load on one wheel, wheel spacings, and total number of main-gear wheels.

The values of the elastic moduli of the pavement layers that are entered into the PAVEVAL computer program were the same as those used in the computer program SUBE with the exception that the Young's modulus of AC pavements and base materials was chosen to have the value E = 31 000 MPa (450 000 lbf/in^2) in the PAVEVAL program for the numerical calculations described in this paper. This value of Young's modulus was obtained from Figure 3 and corresponds to an assumed average annual pavement temperature of 21°C, a value of temperature that was chosen so that the results obtained by using the PAVEVAL program could be compared with the results obtained by using the DSM evaluation procedure. However, the PAVEVAL computer program has a greater capability for pavement-evaluation purposes because it can be used to study the seasonal variation of the pavement load-carrying capacity by using Figure 3 to select the proper seasonal value of

Figure 11. Comparison of values of Young's moduli of subgrades: resilient-modulus measurements versus computer program SUBE—various airport sites.



the Young's modulus of the AC pavement layers. For this purpose, the seasonal variation of the Young's moduli of the base, subbase, and subgrade must also be considered, such as during frost-thaw conditions. The seasonal variation of these Young's moduli values may be determined either by conducting vibratory nondestructive tests during the different seasons or by extrapolating laboratory-measured Young's moduli according to seasonal temperature and moisture changes.

Limiting Stress and Strain Conditions

The load-carrying capacity of an AC pavement and the overlay thickness required for its upgrading are related to the limiting tensile strain at the bottom of the AC layer and the limiting vertical strain at the top of

Figure 12. Comparison of values of Young's moduli of subgrades: resilient-modulus measurements versus Shell formula—various airport sites.

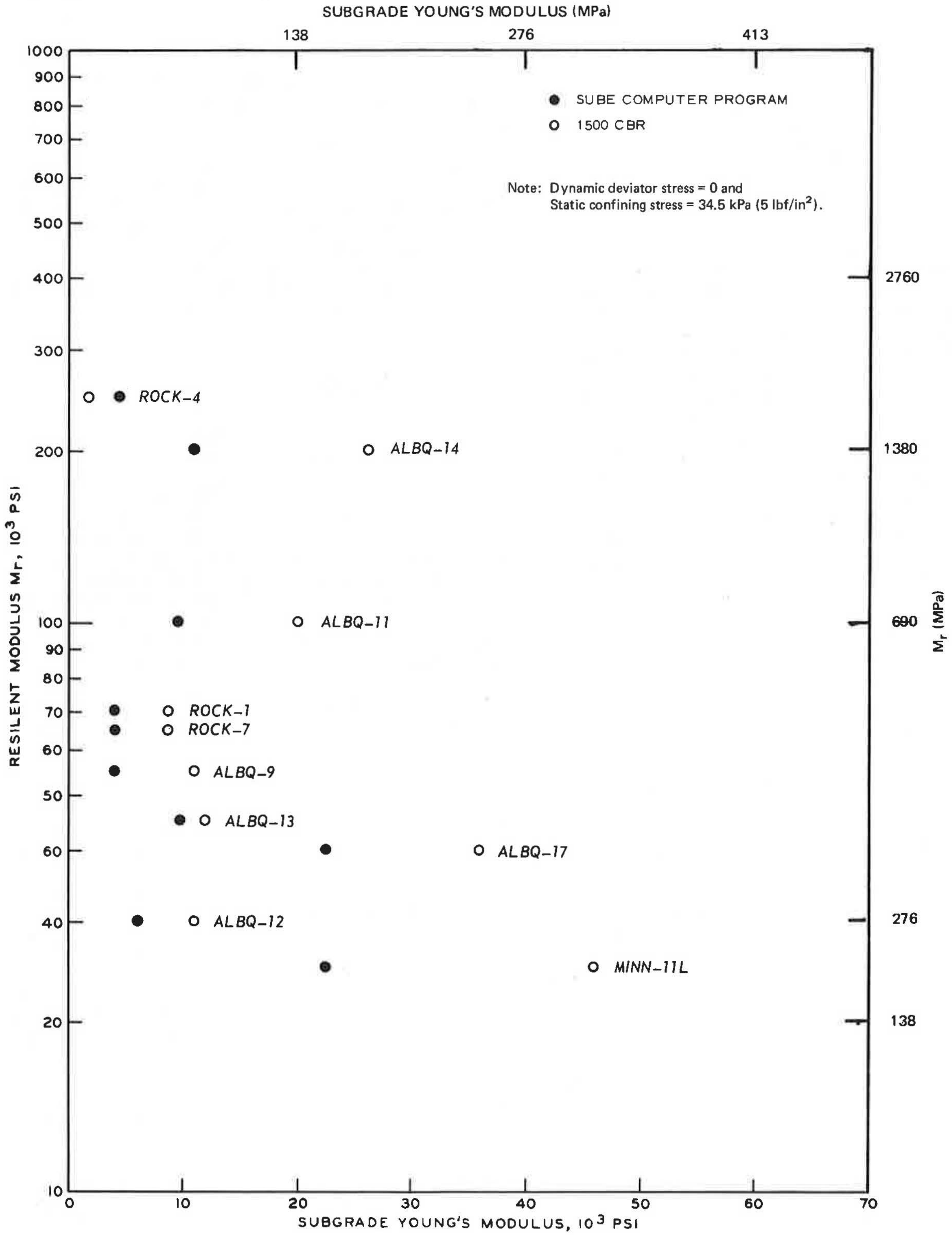
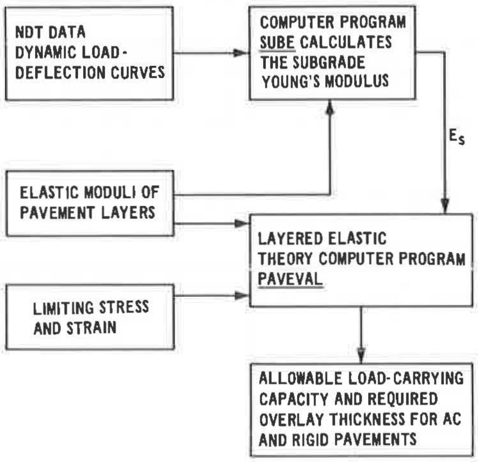


Figure 13. Pavement evaluation and overlay design by method that combines layered-elastic theory and vibratory nondestructive testing.



the subgrade; those of a rigid pavement are related to the limiting tensile stress at the bottom of the PCC layer (11, 12). The limiting value of the vertical strain at the top of the subgrade depends on the number of strain repetitions and on the Young's modulus of the soil in the subgrade (13). The curves in Figure 4 are assumed to be valid for all types of subgrade soils and for single- and multiple-wheel loadings. The limiting value of the tensile strain at the bottom of the AC layer is given by Barker and Brabston (13).

When a load is applied to the surface of a rigid pavement, the maximum tensile stress in the PCC layer occurs at the bottom of this layer and cracking is expected to first occur at this location. The limiting tensile stress is expressed in terms of the number of load (stress) repetitions and of the flexural strength of the PCC layer as follows (15):

$$\sigma_{RL} = R/[A + B \log(COV)] \quad (26)$$

where

R = flexural strength (lbf/in^2),
COV = number of coverages,
A = 0.58901,
B = 0.35486, and
σ_{RL} = limiting value of tensile stress (lbf/in^2).

This expression is assumed to be valid whether the stress in the PCC layer is produced by single-wheel or by multiple-wheel loading. The lateral distribution of traffic was handled by using the pass-to-coverage ratios for individual aircraft given by Brown and Thompson (16). For the four types of gear configurations treated in this paper, the pass-to-coverage ratios for PCC pavement are (a) single wheel = 5.18, (b) Boeing 727 (dual wheel) = 3.48, (c) DC-8-63F (dual tandem wheels) = 3.14, and (d) DC-10-10 (dual tandem wheels) = 3.64. Mixed traffic was not considered in this study, but it can easily be incorporated into the PAVEVAL computer program provided that the frequency distribution of the operating aircraft is known.

Single- and Multiple-Wheel Loadings

To determine the load-carrying capacity and the required overlay thickness for a single wheel loading on a pavement surface, the stress and strain due to the single load is compared with the limiting stress and strain values in the pavement and subgrade. The load on one wheel is entered into the computer program PAVEVAL. The maximum values of the stress and strain in the pavement and subgrade occur directly beneath the single-wheel load. The allowable load and the overlay thickness required are determined by requiring that the stress and strain in the pavement directly under one wheel be equal to the limiting stress and strain values.

Actual aircraft loadings on a pavement occur through two or more wheels in close proximity. Dual-wheel (two-wheel) and dual-wheel, tandem-wheel (four-wheel) configurations are commonly used. For the case of multiple wheels, the total strain or stress in the pavement beneath one wheel is affected by the presence of the other wheels. The maximum values of the stress and strain at some depth in the pavement occur at some point between the wheels of the gear configuration but are, to a good approximation, equal to the values of the stress and strain in the pavement beneath one of the wheels of a multiple-wheel configuration. The multiple-wheel calculations are done within this approximation. The PAVEVAL computer program (and the BISAR program on which it is based) calculates the stress and strain at any point in the pavement or subgrade due to a multiple-wheel loading and then compares them with their corresponding limiting values.

Numerical Values of Load-Carrying Capacity and Required Overlay Thickness

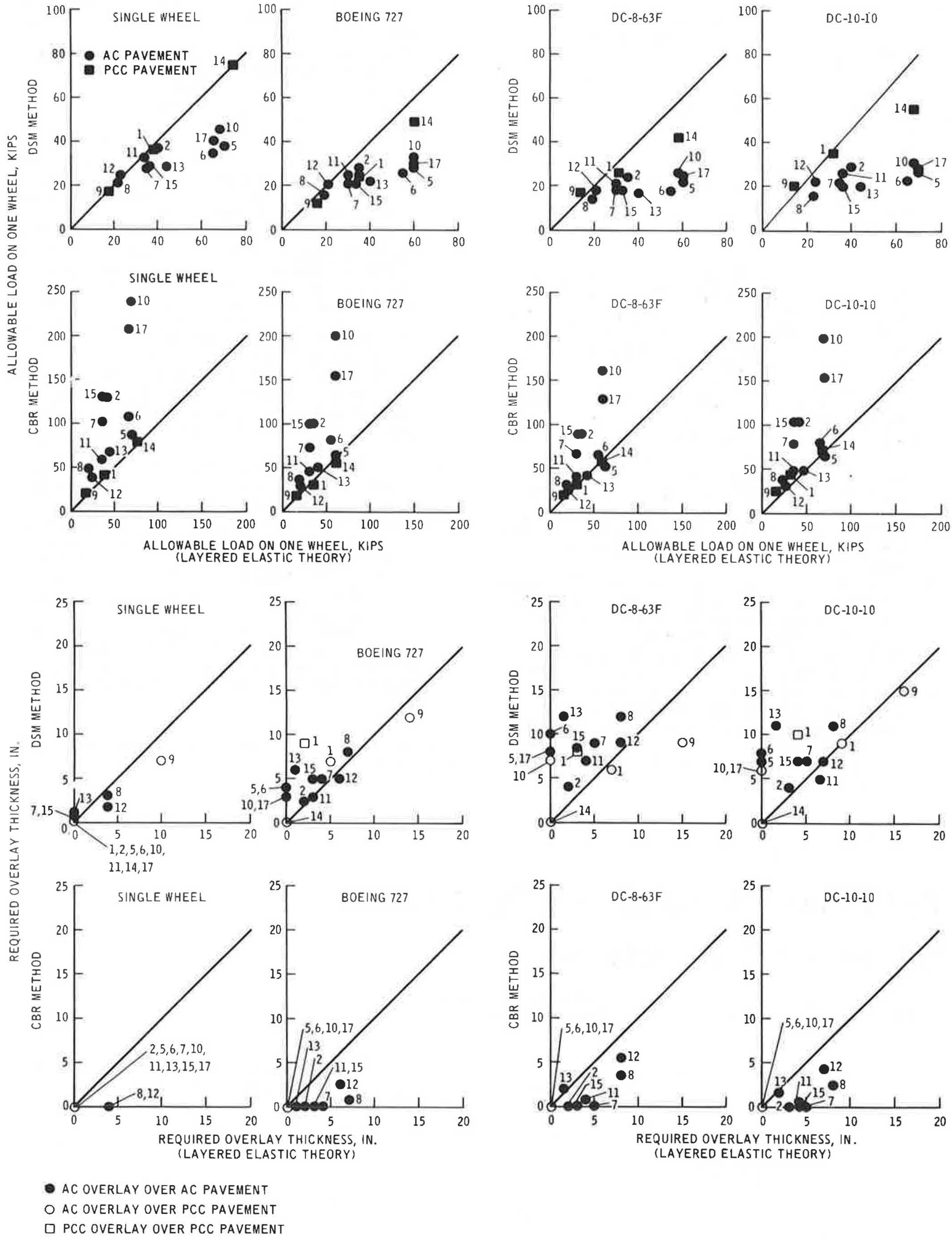
To validate the procedures outlined in this paper, a number of rigid and AC pavement structures were evaluated for single- and multiple-wheel loadings, and the load-carrying capacity and required overlay thickness were calculated. Then, the load-carrying capacity and required overlay thickness were also calculated by the conventional CBR and DSM methods for AC pavements and by the Westergaard and DSM methods for rigid pavements. For the calculation of required overlay thickness, the load on one wheel was taken to be (a) single wheel = 158.53 kN (35 625 lbf), (b) Boeing-727 = 182.85 kN (41 090 lbf), (c) DC-8-63F = 189.17 kN (42 510 lbf), and (d) DC-10-10 = 288.82 kN (51 420 lbf). The results are shown in Figure 14. (The coefficients in Equation 26 were derived for U.S. customary units; therefore, values in Figure 14 are not given in SI units.)

SUMMARY AND CONCLUSIONS

The ability to determine the load-carrying capacity of a pavement and the overlay thickness required to upgrade it is of much importance to pavement engineers. A simple method of pavement evaluation that combines vibratory nondestructive field tests and a theoretical layered-elastic formalism was developed in an attempt to satisfy the needs of the pavement engineer. The layered-elastic-theory approach to the calculation of the required overlay thickness and load-carrying capacity of a pavement requires the value of the Young's modulus of the subgrade, and this value is determined by vibratory nondestructive testing.

For the airfield sites considered, there was only fair agreement between the values of the Young's modulus of the subgrade predicted by the computer program SUBE and those predicted by the E = 1500 CBR method or those determined from laboratory resilient-modulus tests. The exceptionally high values of the Young's modulus predicted by the SUBE program for the Minneapolis-St. Paul test area may be due to the pres-

Figure 14. Comparisons of values of load-carrying capacity and required overlay thickness predicted by computer program PAVEVAL and by CBR and DSM methods: Albuquerque Airport.



ence of bedrock near the surface of the subgrade.

The values of the load-carrying capacity and required overlay thickness obtained by using the PAVEVAL computer program for AC pavements fall in between the values predicted by the DSM and CBR methods. Both the DSM method and the layered-elastic theory method (PAVEVAL) predict load-bearing capacities for AC pavements that are somewhat lower than the values predicted by the CBR method. There is reasonable agreement among the three pavement evaluation methods for PCC pavements. Further study on more airfield pavement sites will be required before more definite comparisons among these three methods of pavement evaluation can be made.

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Pavement Evaluation by Using Dynamic Deflections

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Dynamic test deflections were duplicated by elastic theory by using the Chevron N-layered computer program. Dynamic surface deflections obtained by using the road rater were used in conjunction with elastic theory to analyze pavement behavior. A procedure was developed to use field-measured road rater deflections for the estimation of the elastic modulus of the foundation material and the determination of the equivalent thicknesses of new material that approximate the behavior of the structure. The estimated moduli and the equivalent thicknesses can be used as inputs to design overlay thicknesses. An analysis of the deflections of the first three sensors of the road rater also makes it possible to distinguish weaknesses in asphalt concrete layers from weaknesses in the supporting foundation.

The stiffness of the foundation (subgrade) is one of the factors that affect the behavior of a pavement structure. Variations in subgrade support occur mainly as a result of variations in moisture content or of soil type. A significant decrease in subgrade stiffness (modulus of elasticity) will result in a decrease in ability to support the pavement structure and lead to increased distress in the layers of the structure. Signs of distress are rutting, increased roughness, and cracking (1).

Nondestructive tests have been empirically correlated with field-strength tests. There has been considerable