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Analytical-Empirical Pavement Evaluation Using the Falling Weight Deflectometer

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ABSTRACT

Because of the rapid development of hardware and software during the past 10 years, it is now possible to use an analytical-empirical (or mechanistic) method of structural pavement evaluation on a routine basis. The Dynatest 8000 falling weight deflectometer that, when used with the ELMOD program, determines the modulus of each structural layer in a pavement system is described. The moduli are determined nondestructively and in situ under conditions that closely resemble those under the influence of heavy traffic. Some practical examples illustrating the use of the method are presented, and its empirical components are discussed. These empirical components are also programmed into the ELMOD program so an overlay design may be carried out concurrently with the analytical determination of layered elastic moduli. The method may be used for both flexible and rigid pavements, where joint evaluation is not needed. The evaluation of joint or corner conditions in jointed portland cement concrete pavements is not addressed in this paper.

Structural design of pavement systems should be based on an "analytical-empirical" approach. Often, such an approach is referred to as an "analytical method" or a "mechanistic method," but because it still contains an important empirical component (see the fourth section), the term "analytical-empirical" is more correct. The desirability of an analytical-empirical approach appears to be a universally agreed-on precept among pavement engineers, particularly as a result of the Fifth International Conference on the Structural Design of Asphalt Pavements held in Delft, The Netherlands, in 1982.

The analytical-empirical method presented here makes use of the same approach that is used in most other structural engineering design, that is:

1. The loadings and environmental conditions are determined;
2. The elastic modulus (Young's modulus) is determined for each material in the structure;
3. The critical stresses or strains, as a result of loadings, are calculated in each material; and
4. The thicknesses (or the materials) are modified until the critical stresses or strains do not exceed permissible values.

One reason (of many) for using this approach is the increased need for pavement maintenance and rehabilitation. To make the right choice from many potentially feasible maintenance and rehabilitation measures, the engineer must base his decision on a rational evaluation of the mechanical properties of the materials in the existing pavement structure. To accomplish this, existing empirical methods of pavement design are inadequate. Instead, a combined analytical-empirical evaluation procedure should be followed.

One serious obstacle, however, has been the difficulty of determining the in situ elastic moduli of pavement materials. Three- or four-point bending tests or dynamic triaxial tests are both cumbersome and costly, and the results are not necessarily representative of in situ conditions. Estimating moduli from empirical relationships based on California bearing ratios (CBRs), R-values, or other parameters is hardly satisfactory.

Now, however, the recent rapid development of appropriate hardware and software has made it possible to determine the elastic modulus of each structural layer in a pavement structure. This can be accomplished in situ, nondestructively, and rapidly. With a proper falling weight deflectometer (FWD) and suitably associated software, it is possible to carry out analytical-empirical pavement evaluation on a routine basis. The following is a brief description of one such system, namely the Dynatest 8000 FWD (Figure 1) and the Evaluation of Layer Moduli and Overlay Design (ELMOD) program.

FIGURE 1 Dynatest Model 8000 FWD.

DYNATEST 8000 FALLING WEIGHT DEFLECTOMETER

For a deflection testing device to be used to determine in situ moduli of pavement materials, the following requirements should be met:

1. The load must resemble that of a heavy wheel passage in terms of both load magnitude and duration.
2. Deflections must be measured extremely accurately, especially at distances from 0.6 m (2 ft) to 1.5 m (5 ft) from the center of the loaded area. These deflections are used to determine the modulus of the subgrade and must therefore be accurate because the subgrade generally contributes 60 to 80 percent of the total center deflection. A small error in the determination of the subgrade modulus could, therefore, lead to extremely large errors in the moduli of the other pavement layers. (For the same reason, it is also essential to consider any existing nonlinearity of the subgrade.)

With respect to load magnitude, any appropriate "design" half-axle load (e.g., 9,000 lbf, 50 kN) may be simulated by the Dynatest FWD. A load of more than 10 metric tons (approximately 24,000 lbf) may also be obtained if desired (e.g., for evaluating airfield pavements). The duration of the load is generally fixed at 25 to 30 msec, roughly corresponding to a wheel velocity of 40 to 50 MPH (60 to 80 km/hr). The deflections are measured with geophones at seven different distances from the loading plate, and, because no reference point or support is needed (the reference point is the center of gravity of the earth), the deflections may be determined quite accurately. A typical accuracy is 0.5 percent ± 1 μm (1 μm = 1/1000 mm = 0.04 mil).

On many occasions, pavement response in terms of stresses, strains, and deflections from an FWD-imposed load has been compared to the response to a moving wheel load. Details of some of these comparisons may be found elsewhere (1-3). All these comparisons have shown that the response to an FWD test is quite close to the response to a moving wheel load of the same magnitude, even though the impulse load of the FWD, in some respects, differs from a moving wheel load.

If, therefore, an accurate deflection basin is measured under an FWD test and then the theory of elasticity is used to determine the elastic moduli of the individual layers such that the same deflection basin is produced, the engineer can be reasonably certain that the layer moduli thus obtained will be representative of the response of the pavement materials under heavy traffic loading, even though, strictly speaking, the analysis technique is quasi-static whereas the loading is dynamic.

Details of the Dynatest FWD test system may be found elsewhere (4), but it may be added here that the production capacity is some 200 to 300 test points per day, depending on the distance between points, and that more than 30 of these test systems are now in operation (mostly in North America and Europe).

CALCULATION OF ELASTIC MODULI

Pavement sections are not composed of ideal elastic materials. In addition to elastic deformations, most pavement materials exhibit plastic, viscous, viscoelastic and/or viscoplastic deformations under load, and in most cases the relationships between load and deformation are nonlinear. Many materials are anisotropic, often as a function of the state of stress, and few materials are homogeneous--some are even "particulate," consisting of significantly large, discrete particles. Adding to this the variability of the materials with time and place and the dynamic loading conditions, it should be clear that layered elastic theory is just an approximation of "real-life" conditions.

Nevertheless, this approximation of reality offers, at the present time, the most promising approach to reaching a more fundamental understanding of the performance of pavements. For this reason, elastic theory has been incorporated into a number of current design methods, such as those by Shell, Chevron, and the Asphalt Institute as well as those implemented by several countries. "Elastic modulus" in this paper should be understood to be an apparent modulus or effective stiffness.

To determine moduli, programs developed by Chevron, Shell, and the Laboratoire Central des Chaussées as well as several other institutions may be used. However, the method of equivalent thicknesses (MET) (5,6) used in the ELMOD program is at least as reliable and effective as the other, more sophisticated programs for use on FWD-generated test data. There are two primary reasons for this:

1. First, a mainframe computer is not needed. The calculations can be rapidly carried out on a microcomputer. This means that each FWD deflection basin, instead of just a few "representative" or average basins, may be analyzed. Even more important, the MET may be easily incorporated in a pavement management system, under which critical stresses or strains may have to be evaluated literally millions of times.

2. Second, and most important, it is quite easy to incorporate a nonlinear, elastic subgrade into the MET procedure, and this is essential for determining even reasonably accurate layer moduli from measured FWD deflections, because of the lateral variation of subgrade modulus under load. This procedure is discussed in detail elsewhere (7).

The basic assumption in the MET is that the stresses, strains, and deflections below a given layer interface depend on the stiffness and thickness of the layers above that interface. This concept is used to transform a layered structure into an equivalent uniform, semi-infinite material, to which Boussinesq's simple equations may be applied.

There is a certain resistance against using this relatively "simple" method today because a number of "exact" elastic layered programs are readily available. It should not be overlooked, however, that the assumptions on which these "exact" programs are based are not really indicative of the actual conditions existing in a pavement structure.

As mentioned previously, deformations under load are not only elastic but also plastic, viscous, and/or viscoelastic. The materials are often nonlinear (stress dependent), anisotropic, and inhomogeneous; some even consist of large, discrete particles (e.g., coarse granular materials). These differences between the idealized assumptions on which layered elastic programs are based, coupled with the complex nature of actual pavement materials, are not mitigated by the use of complex mathematics.

Even though the elastic layer programs cannot be considered more exact than the MET when it comes to the behavior of real pavements, the MET has, on a number of occasions, been compared to different elastic layer programs (6). In general, the results have indicated a reasonably good agreement for deflections and stresses, and somewhat less satisfactory agreement for strains.

ELMOD Program

Using FWD-derived load deflection data, the structural evaluation may be carried out with the ELMOD program, which is based on the MET. This program operates on the same microcomputer that controls the FWD field operation. An IBM personal computer version of the program is also available.

The FWD measures the force applied to the pavement plus the deflections at seven different distances from the loading plate. During testing, these values are stored on magnetic tape and later are read by the ELMOD program. In addition, the thicknesses of the structural layers in the pavement must be input (Figure 2). A two-, three-, or four-layer system may be specified.

The ELMOD program will then automatically determine the layer moduli that will produce the same deflection basin as measured. During this iteration, the program also determines any actual or apparent nonlinearity of the subgrade. The lateral variation of subgrade stress is considered and, therefore, the subgrade may be treated as a single, nonlinear elastic layer. This nonlinearity is extremely important in facilitating a reasonably accurate determination of both the subgrade and the remaining, overlying structural layer moduli.

A series of checks was made to compare the ELMOD program with the CIRCLY computer program (8). For 42 different three-layer structures, the surface deflections corresponding to a standard FWD load were calculated with CIRCLY at distances 0, 1.5a, 2a, 3a, 4a, 6a, 8a, and 10a, where "a" is the radius of the loaded area. The range of employed layer moduli and thicknesses was as follows:

E_1/E_3 = 10, 20, 50, 100, 200, 400
h_1/a = 0.5, 0.67, 1, 1.33, 2, 2.67, 3.33
E_2/E_3 = 3
h_2/a = 2

where

E_1 = modulus of Layer 1,
h_1 = thickness of Layer 1,
E_2 = modulus of Layer 2,
h_2 = thickness of Layer 2, and
E_3 = modulus of the (semi-infinite) subgrade.

In all calculations it was assumed that the FWD load was uniformly distributed over a circular area; that all materials (layers) were homogeneous, isotropic, and linear elastic; and that all had a Poisson's ratio of 0.35. All interfaces were considered "rough" (no slip between layers).

The calculated deflections were then used as input to the ELMOD program and the moduli of the three layers were calculated. The thickest and stiffest structures, for which both $E_1/E_3 \geq 100$ and $h_1/a \geq 2$, were treated as two-layer structures.

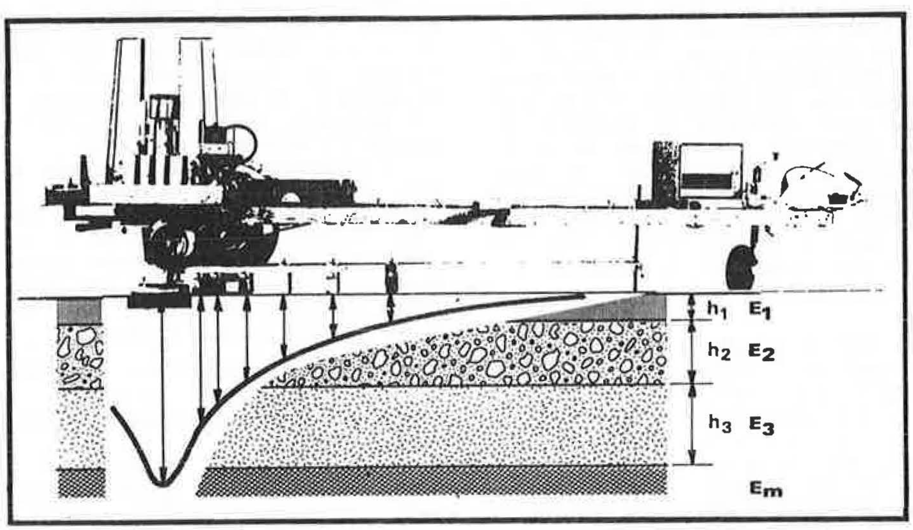

FIGURE 2 Principle of Moduli Determination.

Denoting the moduli obtained with the ELMOD program E'_i and those used as CIRCLY input values E_i, and assuming a log-normal distribution of moduli ratios, the following ratios between ELMOD-calculated and CIRCLY input values were obtained:

	Mean Value	90 Percent Certainty Range
E'_1/E_1	1.01	0.77 - 1.34
E'_2/E_2	1.03	0.70 - 1.52
E'_3/E_3	1.00	0.95 - 1.06

Although the mean values were close to unity, a fairly wide scatter is noted for E_1 and E_2, whereas the agreement for the subgrade modulus (E_3) is extremely good. But even for Layers 1 and 2, the agreement is quite good given that many of the structures were outside the recommended range for use in the ELMOD program and that a coefficient of variation in layer thickness of only 6 percent for Layer 1 and 9 percent for Layer 2 would result in the same scatter. Inaccuracies in assumed layer thicknesses may be quite important for the calculated moduli, but fortunately the layer stiffnesses will still be approximately correct, and therefore the critical stresses and strains calculated subsequently will also be equally correct.

Comparing Theoretical and Measured Values

More important than comparing "exact" layered elastic theory and the MET, is keeping in mind that large differences exist between theoretical models and actual pavement structures. Only by comparing theoretical values to measured stresses, strains, and deflections in situ is it possible to determine whether a given model or approach is satisfactory.

Although deflections may be measured quite accurately in situ, it is much more difficult to measure in situ stresses and strains in a pavement structure. If there is a difference between a measured and a calculated value, there is, at the present time, no way of telling which one is really "correct."

Nevertheless, two comparisons are presented here because they illustrate the type of variations that can be expected between the various theoretical models and measured values of stresses, strains, and deflections:

Example 1

In Figure 3, a comparison of measured and calculated values from two instrumented, full-scale pavements is shown (2). Section 1 was a full-depth asphalt

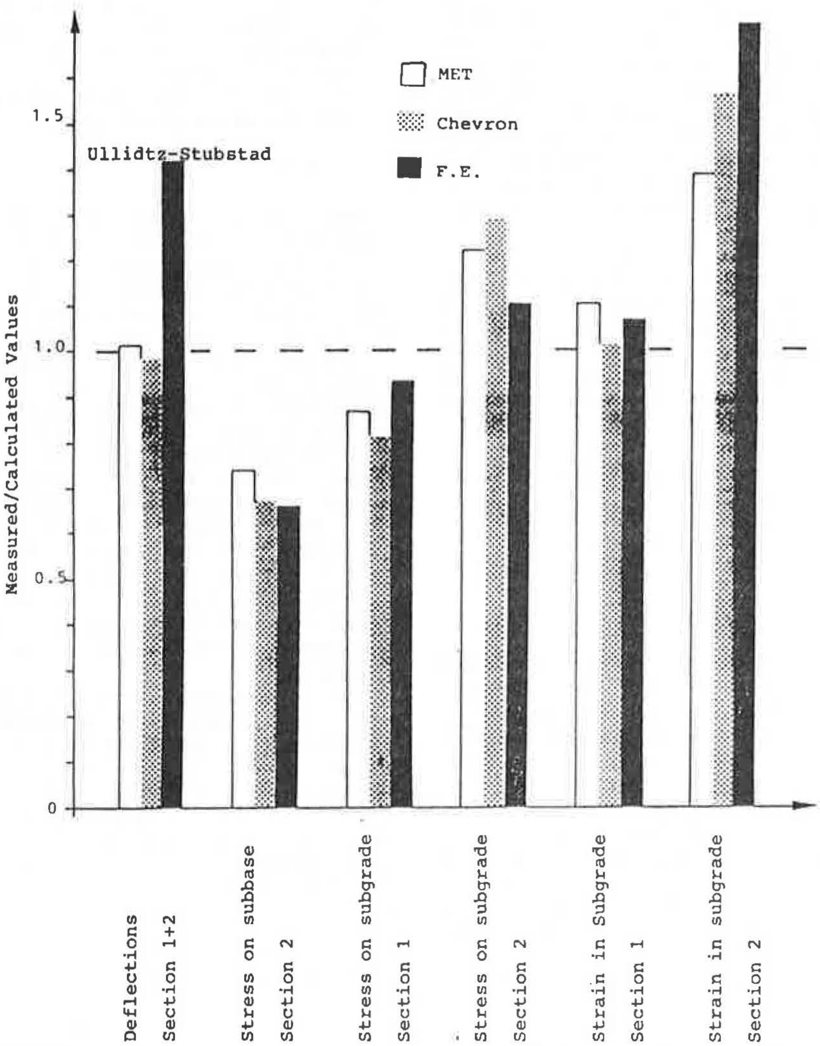

FIGURE 3 The MET, Chevron, and finite element method compared to measured deflections, stresses, and strains.

placed directly on a cohesive (moraine clay) subgrade. Section 2 had, in addition, a granular subbase. Three methods were used to calculate the response: the Chevron program, a finite element (FE) program developed at the University of California, Berkeley (9), and the MET. The input moduli were determined from backcalculations of deflection data using the MET and Chevron approaches and from three-point bending tests on the asphalt materials and triaxial tests on the unbound materials for the FE program input.

Four test series were carried out under different climatic conditions. The results shown in Figure 3 are the mean values of the ratio of measured versus calculated values from all tests conducted. There is a considerable scatter between measured and calculated values and the various methods of calculation, but there is clearly no indication that the MET is any less "correct" than any of the other methods.

Example 2

Comparisons of measured and calculated strains were made by the Organization for Economic Co-operation and Development (OECD) Common Measurement Program Group at Nardo. As a part of the OECD Road Transport Research Program, a Scientific Expert Group on Full-Scale Pavement Tests was formed. The main purpose of this group is to investigate possibilities for coordinating the extremely costly, full-scale pavement testing presently being carried out, or planned for the near future, by member countries of the OECD.

The Common Measurements Program Group, consisting of nine teams from eight member countries, conducted measurements of horizontal strains in the asphalt layer of a test road under heavy truck traffic. More than 200 strain gauges were installed. Details of the experiments and results thereof are to be published by the OECD.

FWD measurements were also carried out at one of these OECD test sites on April 11 and 12, 1984. Using the results of these tests, strains at the bottom of the asphalt layer were calculated with the MET and compared to the values measured under truck traffic. The team from the Technical University of Denmark found the following ratios between measured and calculated strains:

Date	Measured/Calculated Strains
April 11	1.10
April 12	0.93 to 1.07

Conclusion on Calculation of Moduli

On the basis of approximately 20 years' experience with FWD testing, it can be concluded that the layer moduli of a pavement structure can be determined reasonably accurately from FWD test results and that these moduli may be used to calculate the critical stresses and strains in a structure under heavy traffic.

The complex nature of pavement structures and the inadequacy of existing theoretical models, however well computerized, should be realized. More realistic models, like the distinct element method (10), should be developed, but at the present time it does not appear that the mathematically more complex methods offer any important advantages over the more simple method of equivalent thicknesses (except, perhaps, in special cases).

The analytical part of the analytical-empirical method may, therefore, be used with a reasonable degree of confidence, and because it is based on fundamental physical principles it may be used with all types of materials, environments, loadings, and so forth. Of course, the approximations made in the theoretical approach discussed previously should be kept in mind.

RESIDUAL LIFE AND NEEDED OVERLAY

Theoretical models like VESYS (11) and MMOPP (12) may be used to predict future pavement performance in terms of roughness, rutting, and cracking. Because of the large number of input parameters required, however, these models are not well suited for routine purposes. Instead, it appears to be necessary at the present time to rely on empirical relationships between pavement response (i.e., to load) and pavement performance.

Two relationships are generally used, one for predicting cracking of bound layers and one for predicting permanent deformations (roughness or rutting). Preferably, the two predictions should be interrelated so that the predicted structural deterioration (cracking) is considered in the model for predicting functional deterioration (roughness and rutting), but this is seldom attempted or even suggested. It should be noted that the words functional and structural are used to describe two distinct types of pavement condition. Thus, functional condition relates to ride quality and structural condition to bearing capacity. The words are not used to indicate the reason for a specific kind of deterioration, as is sometimes suggested.

Most of the empirical relationships used today are of the exponential form:

$$N = K \times S^a \tag{1}$$

where N is the number of loads to cause a certain deterioration at a stress or strain level (S) at the critically loaded position in the layer and K and a are constants, depending on the type of material and the environmental conditions. In the ELMOD program, equations of this type are used with K and a as user-controlled input parameters. Seasonal variations of the critical stresses and strains are also considered. As many as 12 "seasons" may be specified in the program, and the moduli of all layers (including the subgrade) may be varied with season. The damage caused in each season is calculated and summed using Miner's law. The design wheel load may be a single wheel, a dual wheel, or two dual wheels in tandem (useful for airfield pavement design). The effect of previous loads may or may not be subtracted, as specified by the program user. The positions at which the critical stresses or strains are evaluated by ELMOD under a dual wheel are shown in Figure 4.

If the residual life of a pavement is insufficient, the program will determine the needed overlay thickness of a given material to satisfy Equation 1, as specified for each layer in the structure. The needed overlay thicknesses along the length of the roadway may be plotted or a special routine may be used to automatically divide the roadway into uniform subsections, each with its unique design life and most representative FWD test point. An example ELMOD output is shown in Figure 5.

Structural Deterioration

A vast amount of literature exists on fatigue cracking of bituminous- and cement-bound materials. Usually, the horizontal tensile stress or strain at the bottom of the layer is assumed critical. In prac-

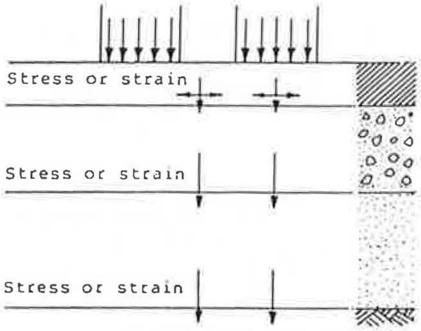

FIGURE 4 Possible location of critical stresses or strains under a dual wheel load.

tice, however, cracking of an asphalt layer has often been found to originate at the top of the layer not at the bottom. A few theoretical studies have been made of this phenomenon (13,14), but no method suitable for routine purposes appears to have been developed yet.

When the maximum tensile stress or strain at the bottom of a bound layer is used, the relationship with performance should be based on empirical evidence (i.e., actual experience) with existing pavements because correlations between the results of laboratory fatigue tests and performance of existing pavements have been rather unsatisfactory. Brown et al. suggest a factor of 100 (15) or 440 (16,p.38) to get from laboratory to in situ fatigue life of asphalt-bound layers, and Thrower (17) has calculated

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FILE ST 1.3 TO 3.9 ON 85/1/9

ROAD No  128  /OUTERWHEEL

LAYER NO. 1 CONSISTS OF
 4 IN ASPHALT
LAYER NO. 2 IS  6 IN THICK
LAYER NO. 3 IS  12 IN THICK

ΔPSR=  5

EQUIVALENT GEARS/LANE/SEASON

SEASON      ESGL
   1        75000
   2        75000
   3        75000
   4        75000

********************************

E-VALUES,ksi 85/1/9

  ST       E1   E2   E3    EM

  3.10  391    38    23   11
  3.30  214    29    17    8
  3.50  271    25    15    7
  3.70  325    20    12    8
  3.90  148    33    20   10

********************************

NON-LINEAR PARAMETRES
85/1/9

  ST     C0     N

  3.10    8 -0.15
  3.30    6 -0.14
  3.50    6 -0.15
  3.70    7 -0.08
  3.90    9 -0.09

********************************

REMAINING LIFE ΔPSR=  5

  ST     LIFE  CRITICAL FAILURE
         YEARS  LAYER     MODE

  3.10    1.5    2      FUNCTIONAL
  3.30    0.2    1      STRUCTURAL
  3.50    0.2    1      STRUCTURAL
  3.70    0.2    1      STRUCTURAL
  3.90    0.2    1      STRUCTURAL
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MODULI FOR EACH SEASON,ksi

 S    ST      E1    E2    E3    EM
 1    3.10   438    38    22    10
 2    3.10   317    52    31    14
 3    3.10   184    62    37    17
 4    3.10   257    49    29    14

 S    ST      E1    E2    E3    EM
 1    3.30   240    29    17     8
 2    3.30   173    40    24    10
 3    3.30   101    48    29    13
 4    3.30   141    37    22    10

 S    ST      E1    E2    E3    EM
 1    3.50   304    24    15     7
 2    3.50   220    34    20     9
 3    3.50   128    41    24    11
 4    3.50   179   -32    19     9

 S    ST      E1    E2    E3    EM
 1    3.70   365    20    12     8
 2    3.70   264    27    16    10
 3    3.70   153    33    20    12
 4    3.70   214    26    15    10

 S    ST      E1    E2    E3    EM
 1    3.90   166    33    20     9
 2    3.90   120    45    27    13
 3    3.90    70    55    33    16
 4    3.90    98    43    25    12

********************************

NEEDED OVERLAY THICKNESS  IN

 ST        OVERLAY
             IN

 3.10        1.22
 3.30        3.07
 3.50        2.99
 3.70        3.15
 3.90        3.35
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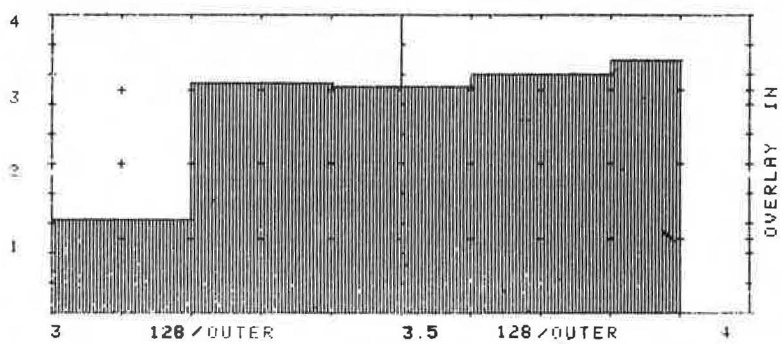

FIGURE 5 Sample ELMOD output.

factors of up to 5000. Full-scale testing with the Danish Road Testing Machine (3) and at the University of Nottingham (18) has shown similar differences between the results obtained on laboratory specimens and on full-scale asphalt pavements.

For cement-bound materials, the power a in Equation 1 is usually reported to be between -20 and -30 based on laboratory tests, whereas the AASHO Road Test showed a power of -4 and Road Note 29 indicates a power of about -3.

Great care, therefore, should be exercised when selecting the constants K and a in Equation 1. With the ELMOD program, these values are user controlled, and it is therefore possible to "calibrate" the program to suit any specific conditions of materials and climate. Some structural deterioration may also take place in the unbound materials. However, this deterioration does not appear to be quantifiable at the present time.

Functional Deterioration

The purpose of the structural layers in a pavement system is to provide a smooth ride. If the pavement remains smooth, its structural condition is, by definition, satisfactory even if structural deterioration is taking place. Most pavements, however, do not remain smooth. Roughness, or rutting, or both develop as a function of loading and climatic conditions and may or may not be accompanied by true structural deterioration (e.g., fatigue cracking).

Functional deterioration may also be associated with degradation of the wearing course, which is unrelated to structural condition. Such surface deterioration will be in addition to that predicted from the structural condition and must, in most cases, be evaluated subjectively.

Thus, the primary purpose of analyzing a pavement structure using the FWD is to predict the development of the future functional condition. Most of the relationships used today are of the form:

$$N = K \times S^a \times E^b \times (P_I - P_T)^c \quad (2)$$

where

- N = the number of load repetitions to cause the performance measure to change from:
- P_I = the initial level to
- P_T = the terminal level, and
- S = the critical stress or strain,
- E = the modulus of the material, and
- K, a, b, and c are constants.

Again, it is strongly recommended that this "response-versus-performance" relationship be based on experience with the actual pavement structures in the region where it is being applied.

In the ELMOD program, the power c in Equation 2 is assumed to equal 1. The AASHO Road Test results indicated that c is initially close to 1, later becoming rather large. A sudden failure, caused for example by unfavorable conditions during a single season, will result in a large value of c (rapidly increasing rate of deterioration). At the AASHO Road Test, most of the flexible pavements failed during spring thaw. Because the seasons are considered separately in the ELMOD program, it is reasonable to assume that c = 1.

For the remaining constants in Equation 2, Kirk (19) has determined values through an analysis of the AASHO Road Test, resulting in the following equation:

$$N = 440/R \times (\sigma_z/1\text{MPa})^{-3.26} \times (E/160\text{MPa})^b \quad (3)$$

where

- N = number of loads to decrease the present serviceability rating (PSR) by 1,
- R = regional factor,
- σ_z = critical vertical stress on the layer considered,
- E = modulus of the material, and
- b = 3.78 for $E < 160$ MPa or 3.26 for $E > 160$ MPa.

Equation 3 has been found to agree reasonably well with the actual performance of road pavements in many parts of the world and may be used as a first estimate when calibrating the method to new conditions of materials and environment.

CONCLUSION

The analytical-empirical (or mechanistic) method of evaluating pavement structures may now be routinely used. Through the use of a sufficiently accurate falling weight deflectometer and appropriate software, the modulus of each structural layer in an existing pavement may be determined. The moduli are determined nondestructively and in situ under conditions that closely resemble the conditions under heavy traffic loading.

The critical stresses or strains in the structure may then be calculated by analytical methods. Changes in moduli due to seasonal changes in temperature or moisture content may be easily incorporated, and any design load or combination of design loads may be used.

The analytical part of the evaluation (i.e., calculating the moduli and determining the critical stresses and strains for design conditions) may be carried out on a microcomputer using the method of equivalent thicknesses. Except for some special cases, this may be done without any loss of accuracy compared with the mathematically more complex methods. The MET has the additional advantage that it may be incorporated in a pavement management system so that prediction of future performance may be based on the actual existing (as measured) structural condition of the pavements.

The analytical part of the method is based on fundamental physical principles and may therefore be used for any conditions of materials, environment, loadings, and so forth.

The weakest parts of the method are the empirical relationships between pavement performance (roughness, rutting, and cracking) and pavement response (stresses and strains). In many parts of the world, a considerable amount of research has been carried out in this field, and reasonably good relationships have been developed. When using the method for new materials or environmental conditions, however, the empirical relationships must be locally calibrated. Through routine use of the suggested analytical-empirical method, a considerable fund of knowledge has already been collected. At present, more than 35 FWD test systems are in service in North America and Europe (and a few in the Near East and Australia), primarily operated by public highway agencies and research institutions. The increased insight gained through actual use of the analytical-empirical method will undoubtedly facilitate its future development, dependability, and accuracy.

Discussion

Waheed Uddin*

The falling weight deflectometer (FWD) is becoming an increasingly popular device for nondestructive testing of pavements because of its capability of applying variable and overload ranges. Several versions of this impulse-generating device are currently in use (20) (see also the paper by Bush and Alexander in this Record). A simplified approach to analyzing FWD deflection basins for pavement evaluation is favored by many engineers. The ELMOD program, which has been described in several publications, is such an approach. However, the desire for simplification should not overshadow research efforts to determine a precise and exact interpretation of dynamic deflection data. The conclusions in this paper imply that the oversimplified approach of ELMOD is more accurate than the results of the multimillion dollar and statistically designed AASHO Road Test. A comparison of ELMOD results with layered theory analysis for some isolated test sections is described. No details about the test sections are given. The authors admit that there is a wide scatter in the results but do not apply or recommend proper limits to their inferences.

The development of computer programs for multilayered elastic theory and finite element programs has taken place in the last two decades. Furthermore, mechanistic interpretation of NDT data for pavement evaluation is still an area of active research. These research efforts should not be discredited just because the behavior of pavement materials is not truly linearly elastic. The inherent weakness in these conventional procedures is the assumption of a static load instead of the peak force of a falling weight deflectometer. Moreover, ELMOD probably works under the assumption of a semi-infinite subgrade. If a rock layer exists at a shallow depth, considerable error in backcalculated moduli can be expected.

The authors have ignored the dynamic effects of FWD tests. Generally, field evidence shows that the dynamic deflection data from a falling weight deflectometer exhibit considerable variability and device dependency (20) (see also the paper by Bush and Alexander in this Record). Like a moving wheel load, an FWD generates a transient load signal, but loading-mode effects still prevail because of the differences in shape and duration (21) of dynamic signals under the two types of excitation forces. Dynamic loading on a pavement surface causes disturbance in the pavement-subgrade system. If the pavement-subgrade system is assumed to be linearly elastic, a true dynamic analysis of this problem is possible by the application of the theory of stress wave propagation in layered elastic media. For a falling weight deflectometer, a true dynamic analysis will require an examination of the spectrum of frequencies excited by its transient impulse.

Authors' Closure

The authors wish to thank Waheed Uddin for his suggestions and comments on our paper. We certainly agree that the ELMOD program, or any other existing "layered elastic" software for that matter, should not preclude continuing research on the behavior and modeling of layered elastic systems under the influence of (transient) moving wheel and vibratory loads.

Indeed, much work still needs to be accomplished in this area. Many American universities, such as the University of Texas, as well as foreign universities, are presently engaged in such research. It was definitely not the intention of the authors to demean any present or future research in any way. Indeed, it was somewhat discouraging to discover that anyone would read such an intention into this paper.

We would, however, like to take this opportunity to briefly summarize our views on the subject matter addressed by Uddin from a more general point of view in order to put matters somewhat into perspective.

Although the FWD and ELMOD programs certainly have their limitations, some of which Uddin outlined in his comments, we believe we have addressed the primary problems associated with the analytical portion of NDT pavement evaluation and analysis, as follows:

1. Although the FWD does not perfectly simulate the effect of a moving wheel load, it has been shown through a number of research projects (7,22) that the deflections generated by the FWD do indeed correspond well to the deflections generated by an equally loaded moving wheel load. We believe that this renders an ensuing layered elastic analysis quite relevant for the purposes at hand, except in the few cases where the so-called "dynamic" effect becomes predominant due, for example, to the presence of a layer of bedrock relatively close to the pavement surface. Further research and development work on the dynamic effects of FWD loadings is thus indeed relevant--but certainly not critical--because the FWD design minimizes such effects by not exciting the pavement at a single, vibratory frequency.
2. The major drawback of most other iterative, reverse layered elastic procedures is that the typically nonlinear subgrade stress-strain properties are not considered in a horizontal direction, which is the way deflection basins are measured. Because the subgrade generally contributes to more than 50 percent of all deflection readings, this nonlinearity should be considered in most instances in order to arrive at reasonably correct E-values, as explained in our paper. The ELMOD program accomplishes this goal quite effectively.
3. If other pavement layers are also sufficiently nonlinear, the ISSEM4 (23) and MODCOMP2 (24) programs are also available. For bedrock or frozen layers close to the surface, the ELMOD program also contains a subprogram called "ELROC," which calculates the (equivalent) depth to any hard layer, along with the requisite E-values of the materials above this layer.
4. In spite of the inherent drawbacks in this approach, as Uddin has delineated, we are quite sure that the weakest link in the whole process of pavement evaluation in general is the link between mechanistic pavement properties (i.e., E-values, stresses, and strains) and performance. We would recommend, therefore, that the major thrust of research should be directed toward improving the distress models used for this purpose, through both continuing theoretical and applied research, as well as through empirical observations of existing pavements. This problem is, in our view, considerably more important than a "fine tuning" of the analytical procedures involved in FWD testing and interpretation through layered elastic analysis procedures.

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