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Standard Guide for Calculating *In Situ* Equivalent Elastic Moduli of Pavement Materials Using Layered Elastic Theory[1]

This standard is issued under the fixed designation D5858; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers the concepts for calculating the *in situ* equivalent layer elastic moduli can be used for pavement evaluation, rehabilitation and overlay design. The resulting equivalent elastic moduli calculated from the deflection data are method-dependent and represent the stiffnesses of the layers under a specific nondestructive deflection testing (NDT) device at that particular test load and frequency, temperature, and other environmental and site-specific conditions. Adjustments for design load, reference temperature, and other design-related factors are not covered in this guide. The intent of this guide is not to recommend one specific method, but to outline the general approach for estimating the *in situ* elastic moduli of pavement layers.

1.2 This guide is applicable to flexible pavements and in some cases, rigid pavements (that is, interior slab loading), but is restricted to the use of layered elastic theory[2] as the analysis method. It should be noted that the various available layered elastic computer modeling techniques use different assumptions and algorithms and that results may vary significantly. Other analysis procedures, such as finite element modeling, may be used, but modifications to the procedure are required.

NOTE 1—If other analysis methods are desired, the report listed in Footnote 3 can provide some guidance.

1.3 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*[3]

1.5 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

2. Referenced Documents

2.1 *ASTM Standards:*[4]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D4123 Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures (Withdrawn 2003)[5]

D4602 Guide for Nondestructive Testing of Pavements Using Cyclic-Loading Dynamic Deflection Equipment

D4694 Test Method for Deflections with a Falling-Weight-Type Impulse Load Device

D4695 Guide for General Pavement Deflection Measurements

3. Terminology

3.1 *Definitions*—In addition to Terminology D653, the following definitions are specific to this standard:

[1] This guide is under the jurisdiction of ASTM Committee E17 on Vehicle - Pavement Systems and is the direct responsibility of Subcommittee E17.41 on Pavement Testing and Evaluation.

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[2] The concepts of elastic layer theory are discussed in Chapter 2 of *Principles of Pavement Design*, by E. J. Yoder and M. W. Witczak, published by John Wiley and Sons, Inc., 1975.

[3] Corrections or adjustments and a complete discussion of the use of each of these analysis methods with different NDT devices may be found in: Lytton, R. L., F. P. Germann, Y. J. Chou, and S. M. Stoffels" Determining Asphalt Concrete Pavement Structural Properties by Nondestructive Testing," *NCHRP Report No. 327*, National Cooperative Highway Research Program, 1990.

[4] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[5] The last approved version of this historical standard is referenced on www.astm.org.

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3.1.1 *backcalculation*—analytical technique used to determine the equivalent elastic moduli of pavement layers corresponding to the measured load and deflections. The analysis may be performed by any of the following methods: iteration, database-searching, closed-form solutions (currently available only for two layer pavement systems), and simultaneous equations (using non-linear regression equations developed from layered elastic analysis output data). The primary emphasis of this guide will be concerned with the first method; however, many of the ideas pertaining to the use of the iterative concept also apply to the other approaches. An iterative analysis procedure involves assuming "seed" moduli values for a layered pavement structure, computing the surface deflection at several radial distances from the load, comparing the computed and measured deflections, and repeating the process, changing the layer moduli each time, until the difference between the calculated and measured deflections are within selected tolerance(s) or the maximum number of iterations has been reached. Alternatively, the analysis procedure may involve searching through a data base of precalculated deflection basins computed from a factorial of known layer moduli and thicknesses until a basin is found that "closely matches" the measured deflection basin. When analyzing pavement behavior, surface deflections and other responses are typically calculated (in the "forward" direction) from layered pavement analysis programs that use layer moduli as input. In "backcalculation," *layer moduli* are selected and adjusted to ultimately compute surface deflections that best match known surface deflections.

3.1.2 *deflection sensor*—the term that shall be used in this guide to refer to the electronic device(s) capable of measuring the vertical movement of the pavement and mounted in such a manner as to minimize angular rotation with respect to its measuring plane at the expected movement. Sensors may be of several types, such as seismometers, velocity transducers, or accelerometers.

3.1.3 *deflection basin*—the idealized shape of the deformed pavement surface due to a cyclic or impact load as depicted from the peak measurements of five or more deflection sensors.

3.1.4 *equivalent elastic modulus*—the effective *in situ* modulus of a material, which characterizes the relationship of stress to strain, specific to the conditions that existed at the time of NDT testing, that is determined by backcalculation procedures for an assigned layer of known or assumed thickness. The collection of all of these layer moduli will produce, within reasonable limits, the same surface deflections as measured at various distances from the center of the load when entered into a layered elastic pavement simulation model analogous to that used in backcalculation.

3.1.5 *pavement materials*—the physical constituents that are contained in all of the various layers of the pavement system; these layers consist of various thicknesses of placed or stabilized in-place materials for supporting traffic as well as the native subgrade or embankment material being protected.

3.1.6 *resilient modulus of elasticity (M_r)*—a laboratory test measurement of the behavior of a material sample (either an intact core or a recompacted specimen) used to approximate the *in situ* response. Specifically as shown below, the applied cyclic deviator stress divided by the recoverable axial strain that occurs when a confined or unconfined and axially loaded cylindrical material specimen is loaded and unloaded. The resilient modulus is a function of load duration, load frequency, and number of cycles:

$$M_r = \sigma_d / e_r \tag{1}$$

where:

σ_d = the applied deviator stress, and
e_r = the recoverable (resilient) axial strain.

4. Summary of Guide

4.1 A necessary requirement of most overlay or rehabilitation design procedures is some measure of the *in situ* or "effective" structural value of the existing pavement. For years, center-of-load (or maximum) deflection measurements have been used to determine the overall structural effectiveness of the existing pavement to carry load repetitions. The analysis of individual surface deflection values and the deflection shape or "basin" represents a technique that can be used to determine separate estimates of the effective layer properties that collectively describe the overall structural capacity of the pavement system.

4.2 A pavement deflection basin can be induced by a static or dynamic surface load. Some pavement materials are viscoelastic, meaning they exhibit elastic behavior at high rates of loading while viscous flow becomes more significant at very slow rates of loading. For this reason, layered elastic theory is appropriate for dynamic loading; however, it is difficult to verify whether these magnitudes of deflection equate to those measured under static loading. When dynamic loadings are applied, the resulting displacements registered at each of the deflection sensors are also dynamic; however, these peak amplitude values do not all occur at the same time. In a static analysis, such as layered elastic theory, these peak dynamic deflections are analyzed as if they are equivalent in magnitude to the deflections that would occur if a load of "equal" magnitude had been applied statically.

4.3 Layered elastic theory is one of the more common analysis methods being used in the design of flexible pavements and, to a lesser degree, rigid pavements. This guide is primarily concerned with the use of layered elastic theory to calculate the layer moduli in flexible pavements. Various computer programs that use some type of deflection-matching iterative procedure or database searching technique have been developed to estimate the pavement material moduli.[6] This guide discusses the various elements of procedures for calculating and reporting *in situ* layer moduli of the pavement cross-section that could then be used in rehabilitation and overlay design calculations.

[6] The following is a list of some of the backcalculation computer programs that have been developed: MODULUS, ELMOD, ISSEM4, MODCOMP, FPEDD1, EVERCALC, WESDEF, and BOUSDEF. One of the procedures, WESDEF, is available through the U.S. Army Corps of Engineers Waterways Experiment Station. See VanCauwelaert, Alexander, Barker, and White," A Competent Multilayer Solution and Backcalculation Procedure for Personal Computers," *ASTM STP 1026*, November 1989.

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4.4 Presently, there are two distinct categories of analysis methods that may be applied to flexible pavements: quasi-static and dynamic. The quasi-static elastic approaches referred to in this guide, include the Boussinesq-Odemark transformed section methods, the numerical integration layered subroutines, and the finite element methods. As a general principle, the selection of a method for analyzing NDT data to determine layer moduli should be compatible with the analysis procedure that will eventually be used for designing the flexible pavement rehabilitation. That is, if a particular layered elastic computer program is to be used in analyzing the pavements for rehabilitation design purposes, the same computer program (or its equivalent) should be used as the basis for determining the material properties from nondestructive testing of pavements. Similarly, if a finite element procedure is to be used as a basis for design, it also should be used for analyzing NDT pavement data. In summary, it is important to consistently use the same analysis method in both backcalculation and design applications.

4.5 The fundamental approach employed in most iterative backcalculation analysis methods estimating the *in situ* layer moduli is that the solution initiates at the outer deflection sensor location(s) to determine the moduli of the lowest subgrade layer above the apparent stiff layer, that usually has an assigned modulus (see Fig. 1). The calculation sequence progresses toward the center of the basin using the "known" lower layer moduli and the deflections at smaller radial offsets to calculate the moduli of the higher layers. This sequence is repeated in an iterative cycle until a solution is obtained that nearly matches the calculated and measured deflections. When using the database-searching or Boussinesq-Odemark transformed section methods, the sequence may not be the same. In all approaches, layer thicknesses and Poisson's ratios must either be known or assumed. Although the principles of these approaches are applicable to all pavement types (flexible and rigid), some analysis methods are more appropriate for specific pavement types and specific NDT devices.[3] Also, some pavement analysis models are restricted to pavement structures where the strength of layers decreases with depth (for example, cement-aggregate mixtures could not be modeled below a granular base material).

5. Significance and Use

5.1 This guide is intended to present the elements of an approach for estimating layer moduli from deflection measurements that may then be used for pavement evaluation or overlay design. To characterize the materials in the layers of a pavement structure, one fundamental input parameter measured in the laboratory and used by some overlay design procedures is the resilient modulus. Deflection analysis provides a technique that may be used to estimate the *in situ* equivalent layer elastic moduli of a pavement structure as opposed to measuring the resilient moduli in the laboratory of small and sometimes disturbed samples. For many overlay design procedures that are based on layered elastic theory, the resilient modulus is approximated by this equivalent layer elastic modulus, because the equivalent modulus is determined as an average value for the total layer at the *in situ* stress conditions of an actual pavement.

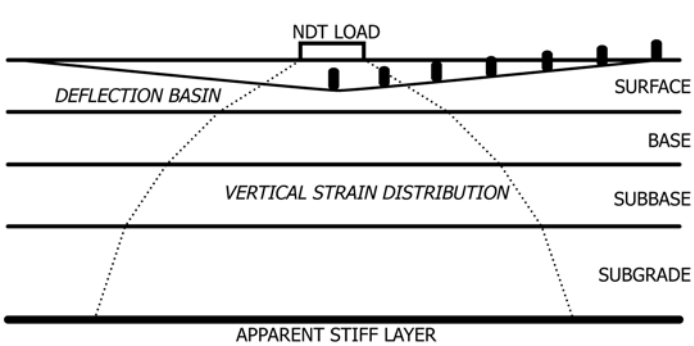

FIG. 1 Depiction of NDT Load Stress Distributed Through Pavement

5.2 It should be emphasized that layer moduli calculated with this procedure are for a specific loading condition and for the environmental conditions at the time of testing. For these moduli to be used in pavement evaluations and overlay design, adjustments to a reference temperature, season, and design load may be required. These adjustments are not a part of this guide.

5.3 The underlying assumption used in the solution is that a representative set of layer moduli exists for the particular loading condition (magnitude and area) and temperature condition, such that the theoretical or calculated deflection basin (using quasi-static layered elastic theory and the assumed static load characteristics of the NDT device) closely approximates the measured deflection basin. In reality, depending on the tolerance allowed in the procedure and the relative number of layers compared to the number of deflection sensors, several combinations of moduli may cause the two basins to "match" (or be within tolerance) reasonably well. A certain degree of engineering judgement is necessary to evaluate these alternative solutions and select the most applicable combination or eliminate unreasonable solutions, or both.

5.4 There have been several studies that compared the results of various types of equipment and analysis methods; unfortunately, considerable variability has been noted. At this time, no precision estimate has been obtained from a statistically-designed series of tests with different "known" materials and layer thicknesses. The backcalculated results do vary significantly with the various assumptions used in analysis to emulate the actual condition as well as with the techniques used to produce and measure the deflections. Since the guide deals with a computerized analytical method, the repeatability is excellent if the input data and parameters remain the same. The bias of the procedure can not be established at this time. The identity of the "true" *in situ* modulus, based on resilient modulus testing or some other field or laboratory test, needs to be standardized before the bias of the method can be established.

6. Analytical Approach

6.1 There are several mathematical techniques based on layered elastic theory that may be used to analyze deflection measurements for determining effective layer moduli in a pavement structure.

NOTE 2—The user is cautioned against using layer moduli that have

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