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16. Abstract

This report presents the development of a user's manual of Dynaflect testing for rigid pavement evaluation. The influence of environmental factors, Dynaflect position, and pavement characteristics on deflections and other sources of errors are discussed as they relate to rigid pavements. Guidelines and specific procedures are also described for determining sample size and application of the Dynaflect deflections to material characterization, void detection, and load transfer evaluation.

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Dynaflect, deflection measurement, rigid pavement, temperature, Young's moduli, voids, load transfer, evaluation

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DYNAFLECT TESTING FOR
RIGID PAVEMENT EVALUATION

by

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Research Report Number 256-6F

The Study of New Technologies for Pavement Evaluation
Research Project 3-8-80-256

conducted for

Texas State Department of Highways
and Public Transportation

in cooperation with the
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Federal Highway Administration

by the

Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

October 1983

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

PREFACE

This is the sixth and final report in the series describing the research work accomplished on Research Project 3-8-80-256, "The Study of New Technologies for Pavement Evaluation." Additionally, this report is also partly based on the research findings of Research Project 3-8-79-249, "Implementation of Rigid Pavement Overlay and Design System." Researchers from both research projects have contributed to the preparation of this report.

This report deals with the background material and development of guidelines for planning Dynaflect testing and analyzing the deflection data for rigid pavement evaluation.

The authors gratefully acknowledge the comments and suggestions given by Dr. T. W. Sager and Dr. Mary Whiteside, Professors of Business Statistics at The University of Texas at Austin during the statistical analyses performed n the Dynaflect deflection data. Thanks are also due to Dr. K. H. Stokoe, for providing guidelines with respect to Rayliegh wave velocities in different soil types. Gratitude is also expressed to Dr. Hani Mahmassani for his invaluable comments regarding the sample size determination of Dynaflect deflections. Appreciation and thanks are also extended to the staff of the Center for Transportation Research for providing support.

The authors also appreciate the acknowledge the support of Gerald Peck, Richard Rogers, and Ken Hankins of the Texas State Department of Highways and Public Transportaton.

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B. Frank McCullough

LIST OF REPORTS

Report No. 256-1, "Comparison of the Falling Weight Deflectometer and the Dynaflect for Pavement Evaluation," by Bary Eagleson, Scott Heisey, W. Ronald Hudson, Alvin H. Meyer, and Kenneth H. Stokoe, presents the results of an analytical study undertaken to determine the best model for pavement evaluation using the criteria of cost, operational characteristics, and suitability.

Report No. 256-2, "Determination of In Situ Shear Wave Velocities From Spectral Analysis of Surface Waves," by J. Scott Heisey, Kenneth H. Stokoe, II, W. Ronald Hudson, and A. H. Meyer, presents a method for determining elastic moduli at soil and pavement sites. Criteria considered in developing this method included the restraint of nondestructive testing, accuracy of moduli for all layers regardless of thickness, and quickness and efficiency for rapid, extensive testing.

Report No. 256-3, "Detection of Cracks on Highway Pavements," by C. H. Chien, W. N. Martin, A. H. Meyer, and J. K. Aggarwal, presents algorithms for the detection of cracks of highway pavements in aerial photographs.

Report No. 256-4, "Evaluation of Moduli and Thickness of Pavement Systems by Spectral-Analysis-of-Surface-Waves Method," by Soheil Nazarian and Kenneth H. Stokoe, presents the Spectral-Analysis-of-Surface-Waves (SASW) method for determination of moduli and thicknesses of pavement systems. The testing procedure is simple, and a unique solution to the problem is obtained.

Report No. 256-5, "Investigations Into Dynaflect Deflections in Relation to Location/Temperature Parameters and Insitu Material Characterization of Rigid Pavements," Waheed Uddin, Soheil Nazarian, W. Ronald Hudson, Alvin H. Meyer, and Kenneth H. Stokoe, II, presents a recommended procedure for removing the influence of any temperature differential in the measured Dynaflect deflections on rigid pavements.

Report No. 256-6F, "Dynaflect Testing for Rigid Pavement Evaluation," by Waheed Uddin, Victor Torres-Verdin, W. Ronald Hudson, Alvin H. Meyer, and B. Frank McCullough. This report recommends step-by-step procedures for making Dynaflect deflection measurements on rigid pavements and for subsequent applications of the Dynaflect deflection data for materials characterization, void detection, and load transfer evaluation.

ABSTRACT

This report presents the development of a user's manual of Dynaflect testing for rigid pavement evaluation. The influence of environmental factors, Dynaflect position, and pavement characteristics on deflections and other sources of errors are discussed as they relate to rigid pavements. Guidelines and specific procedures are also described for determining sample size and application of the Dynaflect deflections to material characterization, void detection, and load transfer evaluation.

KEYWORDS: Dynaflect, deflection measurement, rigid pavement, temperature, Young's moduli, voids, load transfer, evaluation.

SUMMARY

This report describes the development of procedures for monitoring and evaluation of rigid pavements based on the analysis of the Dynaflect deflection measurements. Different factors which influence deflections on rigid pavement are identified and their effects are quantified and discussed. The effect of temperature on deflections near a pavement edge is presented and a procedure for necessary correction is outlined. The extent of the influence of other factors such as distance from pavement edge, voids under concrete slab, and position with respect to transverse cracks is also shown by including appropriate graphs based on theoretical and field studies. Other sources of errors, such as placement and replication errors, variation in slab thickness, and presence of very stiff foundation at shallow depth and their effects on observed deflections are also discussed.

Guidelines step-by-step procedures for collecting and analyzing Dynaflect deflections on rigid pavements are presented for specific applications to (1) materials characterization, (2) void detection, and (3) estimation of load transfer across transverse cracks and joints. A simple procedure for estimating temperature in the concrete slab using information from daily weather reports is presented for use if field measurement of pavement temperature is not possible. The assumption of normally distributed deflections has been checked by making appropriate statistical tests on a random sample of the Dynaflect data and found valid. Detailed guidelines for the selection of a minimum size of Dynaflect deflections for rigid pavement evaluation are also developed and presented.

IMPLEMENTATION STATEMENT

Specific guidelines are included in this report for analyzing deflection data as applied to material characterization, void detection, and estimation of load transfer.

It is recommended that these guidelines be used to generate a user's manual to be used in Texas for taking any future deflection data for structural evaluation of rigid pavements. If data are taken without consideration of these factors their usefulness is limited and the resulting predictions are suspect. Implementation of such a user's manual would be directly beneficial to the Texas State Department of Highways and Public Transportation and the Federal Highway Administration.

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CHAPTER 1. INTRODUCTION

BACKGROUND

Extensive research has been carried out during the past several years to utilize Dynaflect deflections for assessing rehabilitation needs and for design of overlay of rigid pavements. The results of these research efforts are contained in reports generated from past and current research projects at the Center for Transportation Research, The University of Texas at Austin. This document presents an operating manual for the Dynaflect for the evaluation of rigid pavements and reflects the findings of related past and continuing research sponsored by the Texas State Department of Highways and Public Transportation (SDHPT).

Review of the Development of This Manual

The development of this manual for taking Dynaflect deflection measurements draws heavily from research conducted for the SDHPT. Several research reports produced by CTR which have been used in the preparation of this manual are outlined in Fig 1.1.

Research Project No. 177 produced several reports including, a rigid pavement overlay design procedure for Texas SDHPT (Ref 1), a recommended procedure for detection of voids under rigid pavements (Ref 2), and theoretical models for load transfer at cracks (Ref 3). Research Project No. 249 has generated improved procedures for material characterization (Ref 4), an studies on the effect of void size and placement error on measured deflections and determination of sample size for the Dynaflect deflections (Ref 5). Use of deflection to determine the effectiveness of grouting to fill voids under rigid pavement has been discussed in Ref 6.

Effects of temperature and location variables on measured deflections have been investigated in Project 256 (Ref 7). Specific recommendations (1) with respect to distance of Dynaflect tests from the pavement edge, (2) operation of the Dynaflect as related to time of the day, (3) effect of

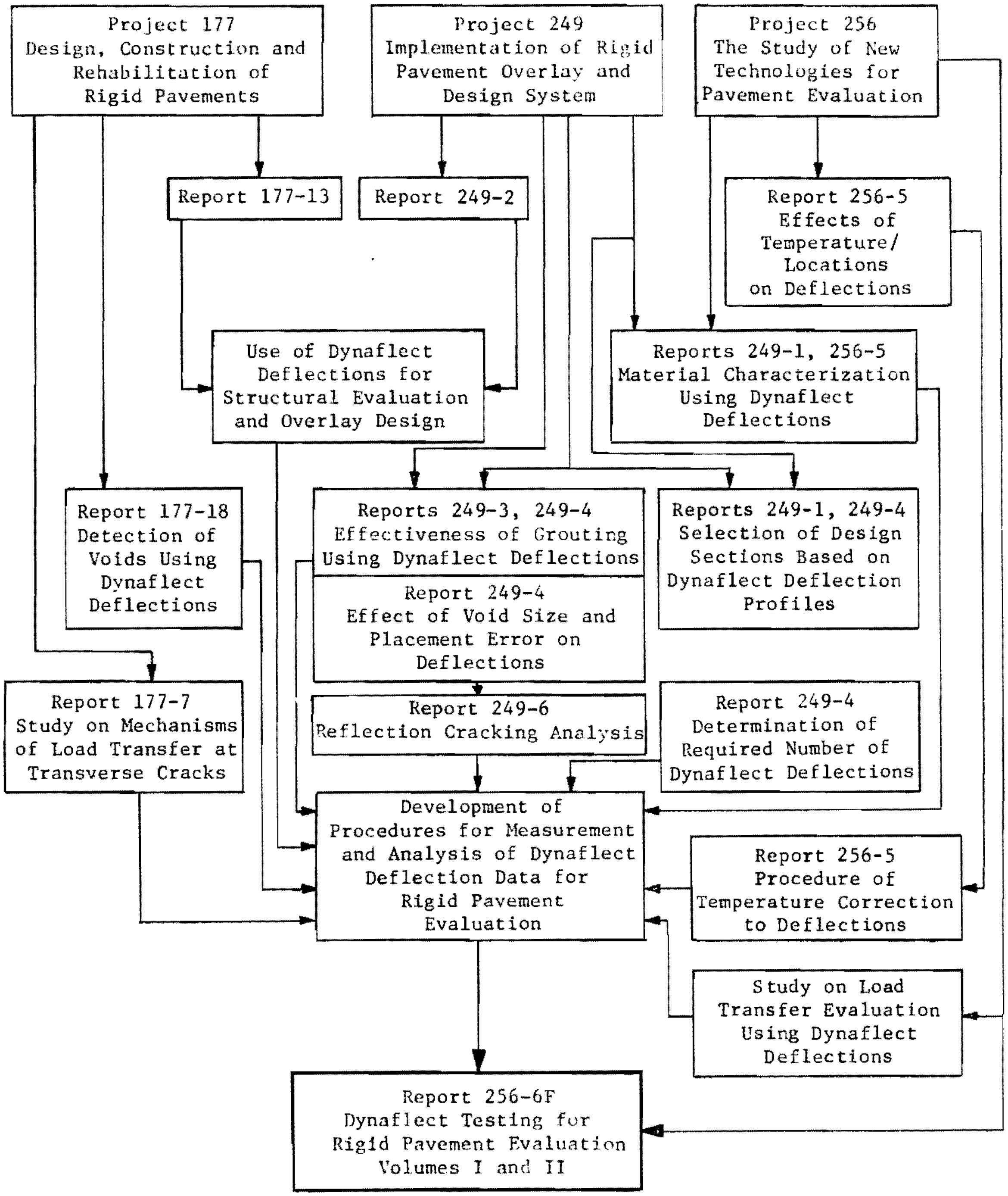


Fig 1.1. A flow chart of contributions from different projects and research reports used in preparation of this user manual.

temperature measurements, and (4) the corrections necessary to remove the significant effect of temperature differential on the measured deflections are based on the findings of Ref 7 and the additional discussions contained in this report. Furthermore, the recommendations made in Ref 7 regarding insitu material characterization procedure are also considered herein.

The Dynaflect System

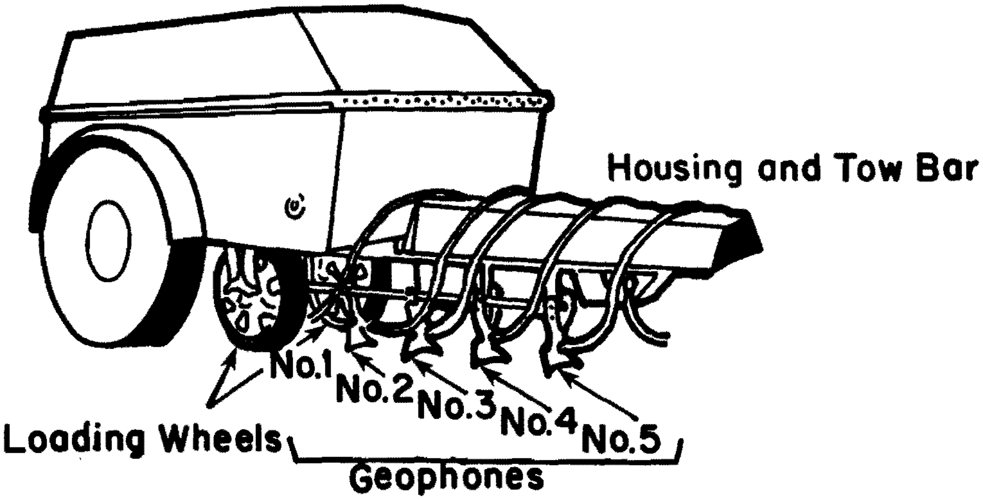
The Dynaflect system (Fig 1.2) and its operating characteristics are discussed in Refs 5, 7, 8, and 9. A comparison of the Dynaflect with some other NDT devices has been made in Ref 8.

Operating Characteristics. The Dynaflect is a trailer-mounted unit which induces a steady state vibratory force on the surface of pavement through two rubber covered steel wheels. The dynamic force generator employs two counter rotating eccentric masses producing a peak to peak dynamic load of 1000 lb at a fixed frequency of 8 Hz.

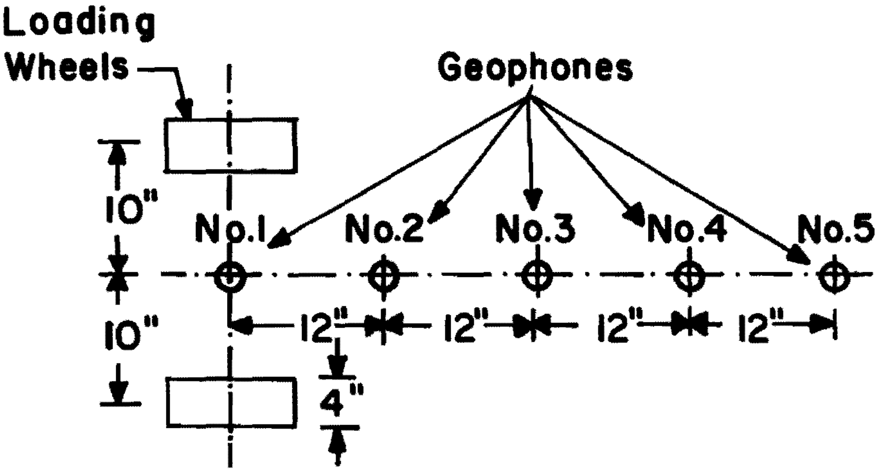
Deflection Measuring System. Five equally spaced geophones are used to measure deflection response of the pavement (Fig 1.2). A sixth geophone is an option that can be hand-placed in any desired configuration. Prior to testing, each geophone is calibrated at the driving frequency, 8 Hz. A geophone is a velocity transducer which employs an inertial reference and gives an output signal in volts. The peak-to-peak dynamic deflection is proportional to the output voltage. The arrangement of five geophones in the automated system of the Dynaflect measures half of the deflection basin. A step-by-step procedure to use the Dynaflect for measuring a deflection basin is described in Ref 7.

Purpose and Use of Deflection Measurement

Structural Evaluation. Monitoring of pavements and the subsequent feedback is an essential requirement of any working pavement management system (Ref 9). Structural monitoring of pavements is desirable before any major maintenance work or if a high level of distress is indicated from the



(a) The Dynaflect system in operating position (Ref 26).



(b) Configuration of load wheels and geophones.

(A sixth geophone is an available option.)

Fig 1.2. Configuration of Dynaflect load wheels and geophones in operating position.

results of condition surveys. On a project level PMS, structural monitoring is performed by making deflection measurements on an extensive basis. The deflection data are then used to divide the length of road in the design test sections. Subsequently the deflection data in each test section are analyzed to estimate the structural adequacy by using an empirical, allowable deflection approach or a mechanistic approach using layered theory computations.

Insitu Material Characterization. The Dynaflect deflection basin measured on an existing pavement is also used to back-calculate Young's moduli for the pavement layers. It is an iterative procedure in which layered theory is used to calculate theoretical deflections under the Dynaflect loading, which is compared with the measured deflection basin. This approach reduces the need for characterization of the pavement materials by laboratory tests (Refs 4 and 7).

Void Detection. The loss of soil support under rigid pavements associated with voids leads to increased load stresses and increased deflections. This will cause significant reduction in the fatigue life of the pavement. To study this problem deflection profile along the pavement edge may be compared with the corresponding deflections in the inside lane. Areas showing large deviations indicate partial loss of support and the possibility of voids (Ref 2). For any rigid pavement rehabilitation program, deflection surveys for the purpose of void detection should be considered as a integral part of the monitoring program.

Load Transfer Evaluation. The monitoring program for an existing rigid pavement can also include deflection measurements across the transverse cracks and/or joints to estimate the adequacy of load transfer. Deflection measurements can also be used with the results of condition surveys for diagnostic checking of the condition of transverse cracks and joints.

OBJECTIVES

General

The Dynaflect deflections are used extensively to monitor rigid pavements. There are several environmental and operational factors that influence measurements of Dynaflect deflections. This report outlines these factors and presents procedures to quantify them. The causes of measurement errors plus the corrective procedures (which may be necessary before the deflection data are analyzed for structural evaluation) are also discussed.

Specific

This report provides specific guidelines for performing deflection measurements for the following purposes.

Material Characterization. Design test sections are delineated on the basis of a preliminary deflection profile. Statistical tests are then used to divide the sections that are significantly different from each other. Procedures are developed in Chapter 5 of this report in order to arrive at a suitable number of deflection measurements in each test section.

The most desirable location of the Dynaflect with respect to pavement edge and transverse crack will be recommended. Procedure for calculation of insitu Young's moduli will also be outlined.

Void Detection. The location of Dynaflect and frequency of deflection measurements will be discussed. Specific recommendations will be made to reduce the effect of temperature on deflections. A procedure to remove the influence of temperature differential on measured deflections will be presented.

Load Transfer. The theoretical models for estimating load transfer across transverse cracks and/or joints are reviewed. Additional analysis is performed in order to estimate any loss in load transfer across the transverse cracks or joints using deflections.

SCOPE OF THIS REPORT

This report presents a detailed operating manual for making reliable and accurate deflection measurements with the Dynaflect for structural monitoring and evaluation of rigid pavements. Separate guidelines are included for each specific use of the data, in this report as described in the following.

Chapter 2 summarizes factors that affect pavement deflections and the findings of previous research efforts. These include environmental factors, temperature effects and seasonal effects. Effects of pavement characteristics such as void size and discontinuities on deflections are presented as one source of errors in deflections -- e.g., placement replication, effect of rigid bottom, and variation in slab thickness.

Chapter 3 is devoted to the applications of deflection measurements in material characterization load transfer estimation and void detection. Chapter 4 presents and briefly discusses a theoretical model for estimating temperature at any depth of concrete slab using information from daily reports on climatological data providing an alternative to the actual measurement of pavement temperatures at the top and bottom of the slabs. Statistical treatment of deflections is dealt with in Chapter 5, which includes tests for normality assumption and determination of sample size for deflection measurements. Chapter 6 summarizes the earlier chapters and presents final conclusions and recommendations.

CHAPTER 2. FACTORS WHICH AFFECT PAVEMENT DEFLECTIONS

Deflection measurements on rigid pavements by NDT equipment are influenced by a number of factors. These factors can be broadly classified into two categories -- (1) environmental factors and (2) pavement characteristics. Other sources of error in measured deflections result from the presence of a rigid rock layer near the surface. The operation of the equipment could also be considered a source of error.

ENVIRONMENTAL FACTORS

Temperature effects, seasonal effects and moisture effects are considered.

Temperature Effects

Review of Past Research. Temperature affects rigid pavement behavior in two ways:

(1) Seasonal variations in temperature cause pavement to contract or expand over a large time interval and affect the development of friction force between the slab and the underlying layer and expansion of joint and crack.

(2) The daily variation of temperature causes temperature differential in the slab and results in curling and warping.

Detailed literature reviews are presented in Refs 7 and 11. In addition conceptual discussion is also made in Ref 5.

Curling and Warping. Behavior of a rigid pavement is influenced by a vertical temperature differential in the slab, as discussed in Ref 7. Temperature differential is defined as the algebraic difference, temperature of top minus temperature at bottom of a concrete slab. The terms curling and warping have been used to define the distortion of the pavement slab from its normal plane (Refs 11 and 12). Price (Ref 10) has done a literature review in order to establish clear definitions of these two terms. In this report, definitions adopted by Price are used.

Accordingly, curling is "the distortion of a pavement slab from its proper plane caused by differential expansion or contraction resulting from a difference in moisture content or in temperature between the top and the bottom of the slab." A temperature differential in the concrete slab will cause curling. Warping is defined as "the distortion or displacement of a pavement slab from its proper plane caused by external forces other than loads." An example of warping is the distortion caused by volumetric changes in the subgrade.

Temperature Effects on Deflections. Reference 7 presents results of an investigation into the influence of temperature and distance from pavement edge on Dynaflect deflection data collected on CRC pavement at Columbus, Texas in summer and fall 1981. The results showed that temperature differential is significant in explaining variation in Dynaflect deflections. It was also concluded that the influence of temperature differential on deflections measured in the wheelpath or in the center of the slab is practically insignificant. However, errors involved in deflections measured at the pavement edge were significant. These findings are also illustrated in Fig 2.1. Another consideration in the evaluation of deflections is the dispersion of scatter of data around the mean. Standard deviation is a measure of dispersion. From the replicate edge deflection data (Ref 7), it has been established that the sample standard deviation of edge deflections is considerably higher as a result of temperature differential, as illustrated in Fig 2.1.

Seasonal Effects

Any seasonal changes in parent deflections are generally the result of seasonal variation of moisture in unbound base layer and subgrade. The seasonal effects on deflections on rigid pavements are thoroughly discussed

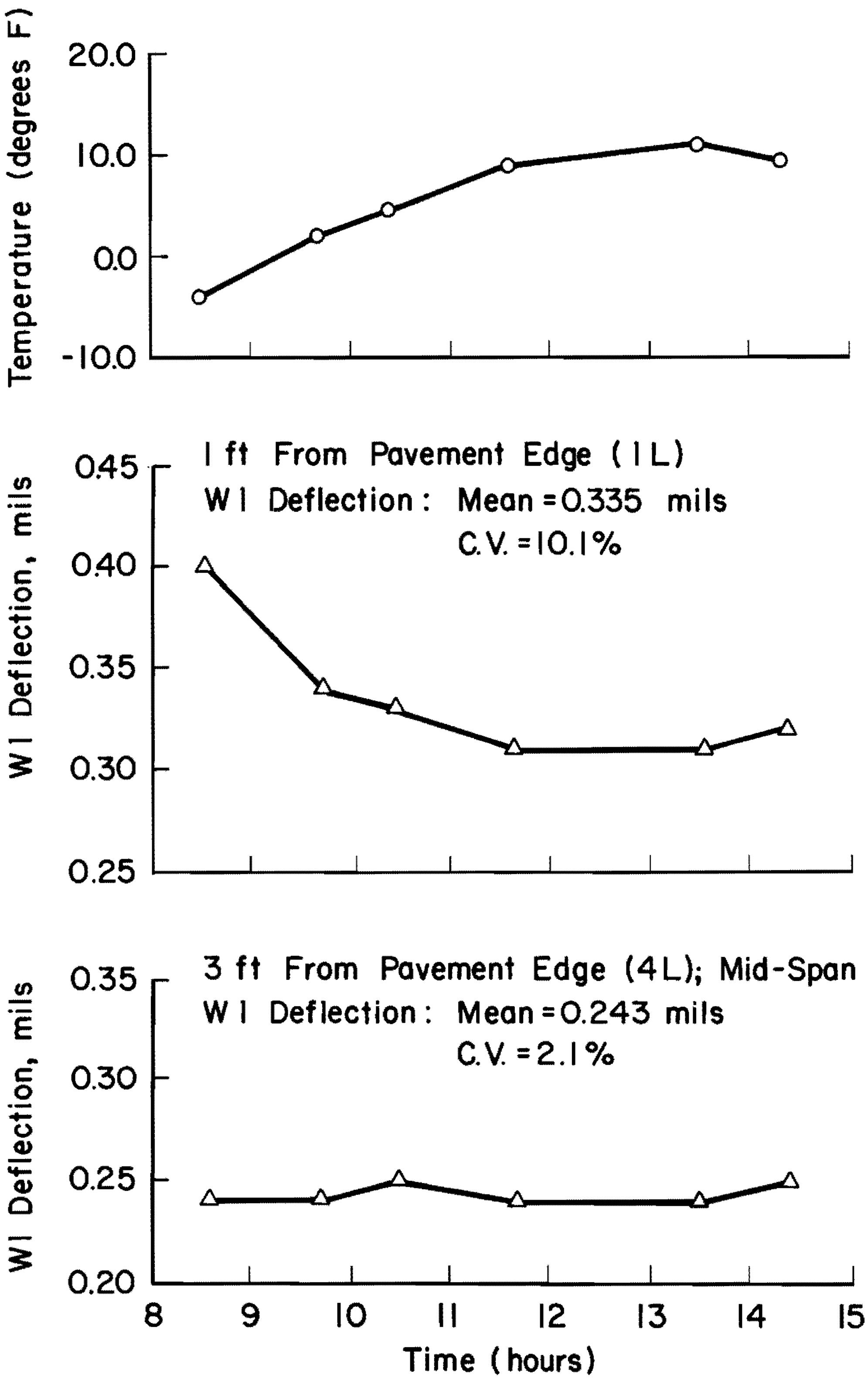


Fig 2.1. Variations in temperature differential and Dynaflect deflections with time on December 1, 1981, at Columbus bypass, SH-71 (CRC pavement; Test Section 3).

in Refs 4, 5, and 7. The results of ANOVA on the Columbus Dynaflect data (Ref 13) show that there was statistically no significant difference in the means of sensor 1 deflections during summer and fall. This finding is also illustrated in Fig 2.2. Metwali (Ref 14) describes the results of ANOVA applied to the Dynaflect deflection data collected during fall and spring on different rigid pavement test sections. Metwali concluded that CRC pavements do not experience appreciable seasonal variations in their deflection. Jointed concrete pavements and asphalt pavements showed statistically significant changes in the maximum Dynaflect deflections due to seasonal variations. These findings by Metwali (Ref 4) are interesting and somewhat in conflict with the current data and belief. Further research is needed in this area.

POSITION OF DYNAFLECT

The position of any NDT device with respect to the pavement edge and transverse crack or joint will greatly influence the measured deflection. Torres-Verdin and McCullough (Ref 5) reported a theoretical investigation using the SLAB49 Computer program (Ref 15) based on plate theory. By modeling the Dynaflect loading, deflections were found to decrease with an increase in distance from the pavement edge (Fig 2.3). Voids were also modeled at the edge. Significantly higher deflections were computed at the pavement edge. The effect of void size is further discussed in a letter section.

The experimental data collected at the Columbus, Texas, bypass and analyzed by Uddin et al (Ref 7) also indicate the significant effect of the distance of the Dynaflect with respect to pavement edge and position with respect to the transverse cracks. These findings are supported by the results of ANOVA (Ref 13) and illustrated in Fig 2.3. It is also shown in Chapter 5 that the normality assumption of the Dynaflect deflection data is valid only if the deflections are considered as sampled from the populations having different means and variances with respect to the distance of the Dynaflect from the pavement edge. In other words, if deflection data are

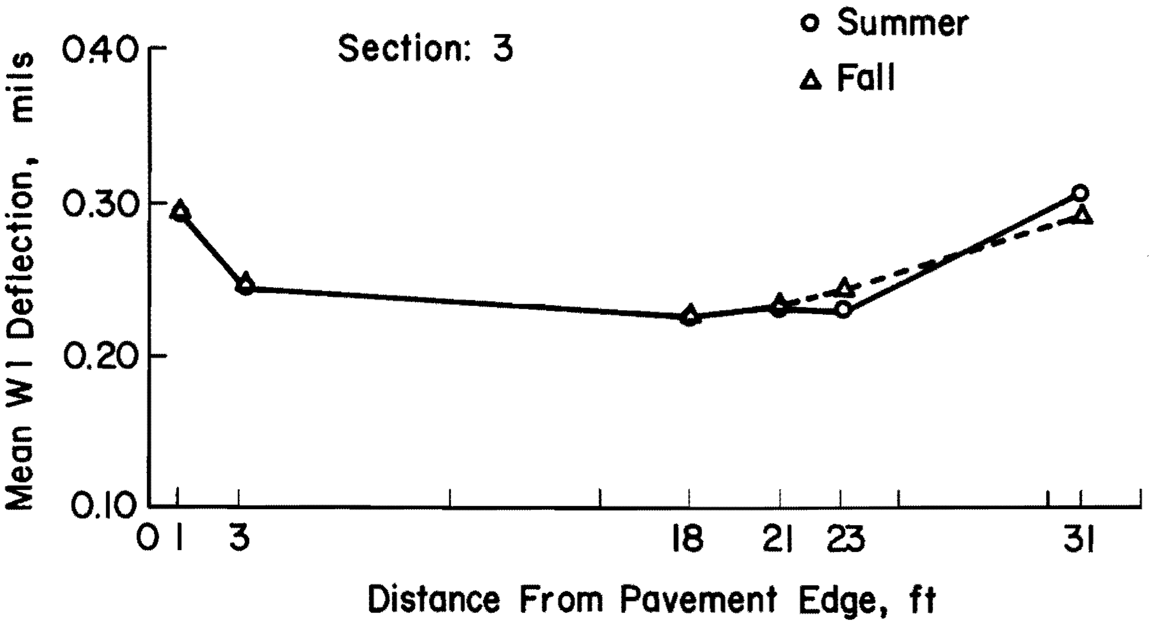


Fig 2. 2. Season effect on mean Dynaflect deflections, CRC pavement, Columbus bypass.

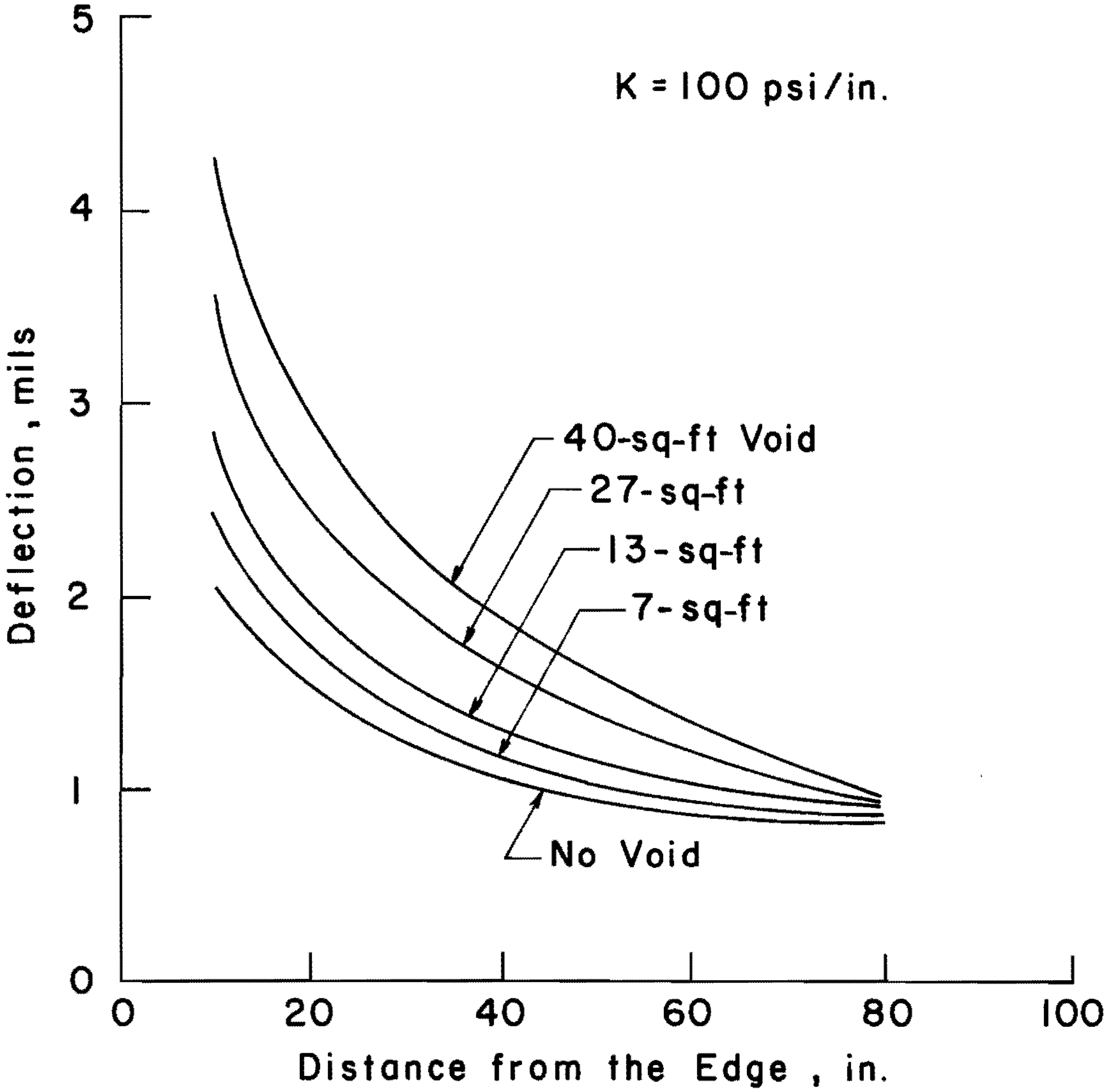


Fig 2.3. Deflection versus distance from the pavement edge for five different void conditions (Ref 6).

used to make statistical inferences, the data collected at different distances from the pavement edge should not be combined.

PAVEMENT CHARACTERISTICS

Basic assumptions in applying elastic layered theory to the design of rigid pavements include infinite slab in all directions away from the load and uniform K (modulus of subgrade reaction) at all points under the slab. A uniform K under the slab is improbable in an old pavement as voids may be created under the slab near its outer edge. Similarly the first assumption is also violated in a rigid pavement due to presence of joints and other discontinuities such as cracks. There are times when these violations may produce unreliable results and this may warrant the use of testing technique which is capable of applying a variable load. Effects of void size and discontinuities on deflections are examined in this section.

Effect of Void Size

Creation of voids under concrete slab can principally occur by (1) pumping of subbase material, (2) movement or differential settlement in subsoil strata, and (3) slab jacking. A detailed discussion of the effect of voids on stresses and deflection and resulting reduction in the fatigue life of the pavement is given in Ref 5. An analytical investigation into the effect of void size on deflections was carried out in Ref 5 by modeling Dynaflect loading between transverse cracks. A factorial design was used to make runs of the SLAB49 computer program (Ref 15). Slab size (23.3 ft x 60.0 ft), crack spacing (8 ft), pavement thickness (8 inches), concrete modulus of elasticity (5 x 10^6 psi), and concrete Poisson's ratio (0.20) were held at fixed values. The parameters varied were (1) K values at 3 levels, 100, 400, and 800 psi; (2) distance of Dynaflect sensor no. 1 from the pavement edge also, at 3 levels 10, 40, and 80 inches; and (3) void size at 5 levels, 0, 7, 13, 27, and 40 sq. ft. The study showed that deflection increased as void area was increased, as illustrated in Fig 2.3. When the Dynaflect is moved toward the center of the slab, deflection decreases and at 5 ft from the pavement edge there is practically no effect of void size on deflection (see Fig 2.4).

Effect of Discontinuities

The presence of discontinuities, such as transverse crack or joints, is an inherent characteristic of rigid pavements. Test load applied near these discontinuities results in higher deflection than the corresponding deflection measured away from the discontinuity. A discontinuity implies reduced slab bending stiffness in the orthogonal direction. Columbus Dynaflect data (Ref 7) provide experimental evidence of significantly higher deflection near the transverse crack as compared to the corresponding midspan deflection (see Fig 2.5). This figure also demonstrates the variations in deflections caused by different types of edge supports. In Fig 2.5 distances are measured from the pavement edge with the inside asphaltic concrete shoulder. The abnormalities in deflection measured at 18, 21, 23, and 31 feet from the pavement edge show the influence of the longitudinal joint located (at 24 feet). Deflections near the longitudinal joint (one foot from the joint which is 23 feet from the pavement edge) are higher than the deflections measured away from this joint. In this study (Ref 13), test section was also found to be a significant main effect. Plots of mean deflection versus distance from edge are similar for sections 2 and 3 but different for section 1. This can be explained by possible changes in the subgrade characteristics. The deflections near the transverse crack will also be affected by temperature changes. This subject is discussed further in Chapter 3, where a procedure is developed to use deflections for load transfer evaluation at transverse cracks.

ERRORS

Effect of Placement Error

The deflections are significantly influenced as distance of the test load is varied from the pavement edge, as illustrated in Figs 2.2 and 2.3 in

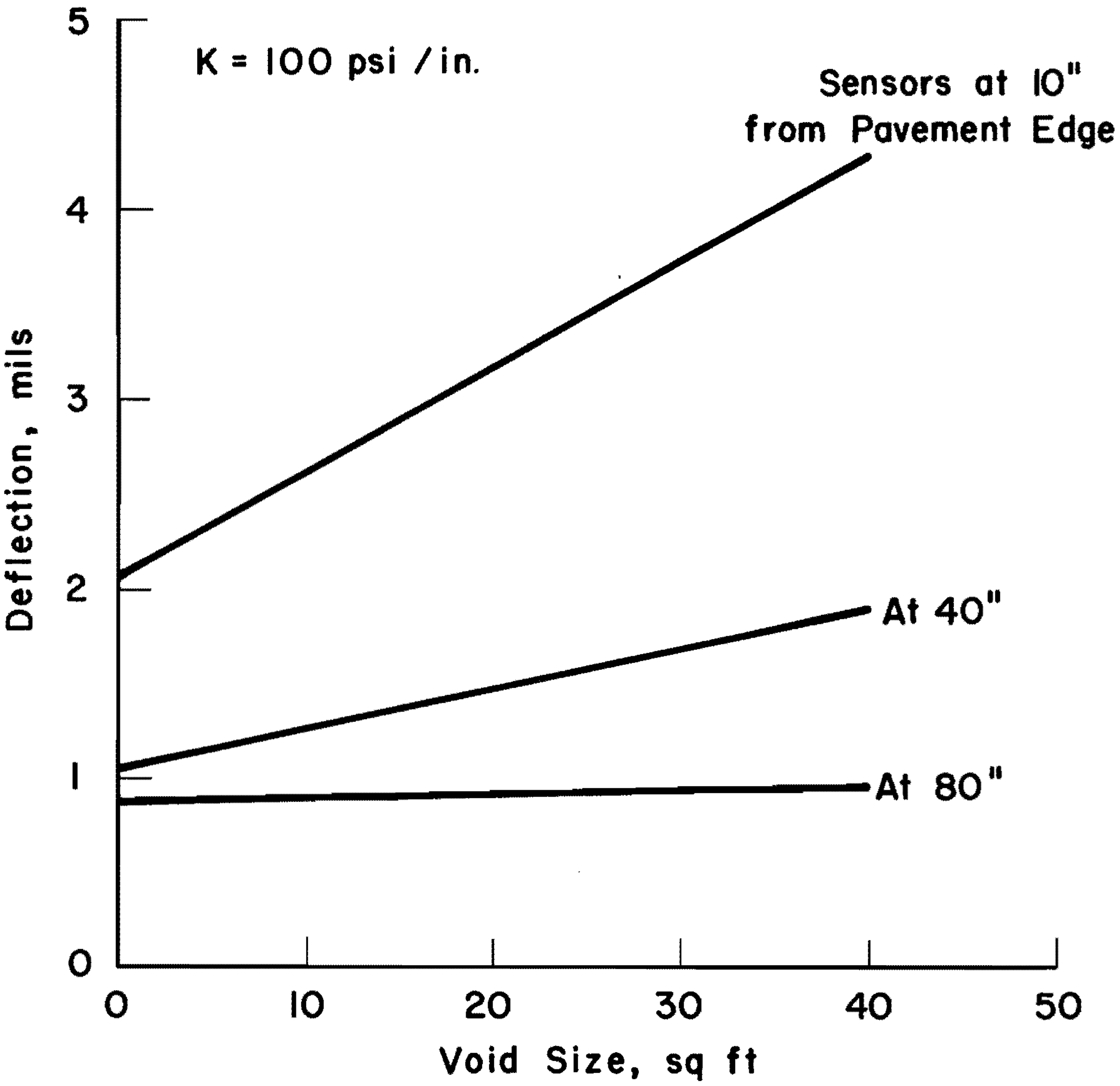


Fig 2.4. Void size vs deflection for three different Dynaflect positions (Ref 5).

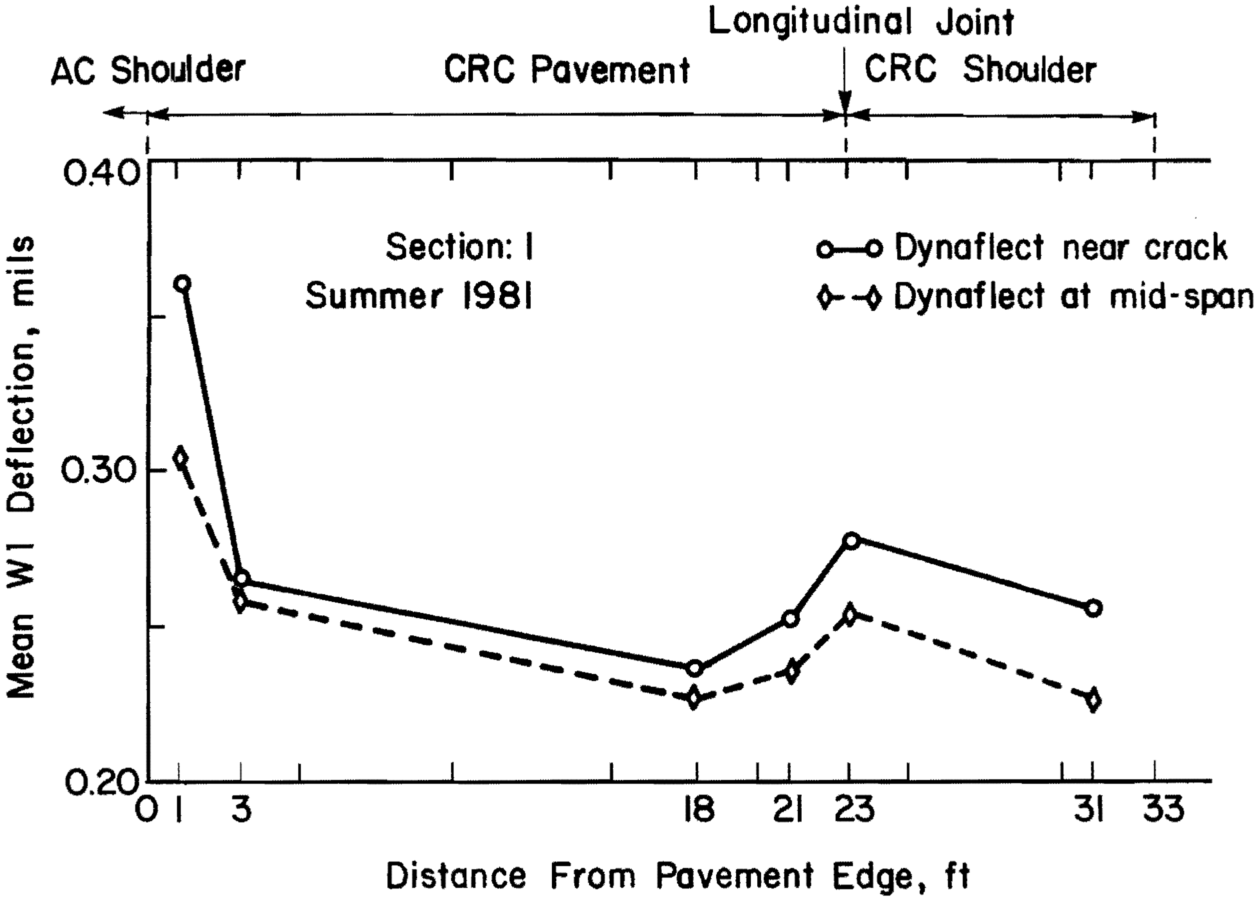


Fig 2.5. Variation in mean W1 deflections at midspan and near crack as a function of distance from the pavement edge.

Refs 5 and 7 respectively. The effect of placement error of the Dynaflect was theoretically analyzed in Ref 5. Placement error was considered to be the difference between the deflection at any distance greater than 20 inches from the pavement edge which results from placing both wheels of Dynaflect on the pavement. Figure 2.6 illustrates typical results of the influence of placement error of the Dynaflect on deflection as a function of void size. The error due to the void size is found to be generally greater than the placement error. It is concluded that the placement error should be kept as small as possible and should never exceed 5 inches.

Replication Error

Replication error is associated with any deflection measuring device. It is also referred to as repeatability of the device. A review of several NDT deflection measuring devices and repeatability is made in Ref 8. Additional discussion and experimental data are also presented by Uddin et al (Ref 7). The coefficient of variation of replicate measurements of the Dynaflect sensor 1 deflections is in general below 10 percent (for locations which are not appreciable affected by temperature) and is as low as 2.1 percent.

Effect of Rigid Layer

If a rigid bottom or rock layer exists at some depth, deflection measurements and subsequently Young's modulus of the subgrade will be significantly affected. Surface deflection is the integration of vertical strain over some depth which is considered to be infinite in most elastic layered theory programs. Presence of a rigid base at shallow depth will result in a reduction in the deflections. But, if the same deflection basin is to be used for calculation of Young's moduli, the subgrade modulus will be significantly overestimated if the rigid base is not modeled in the layered theory program used for basin fitting. Taute et al (Ref 4) made a detailed study of this problem. They developed regression equations that can be used

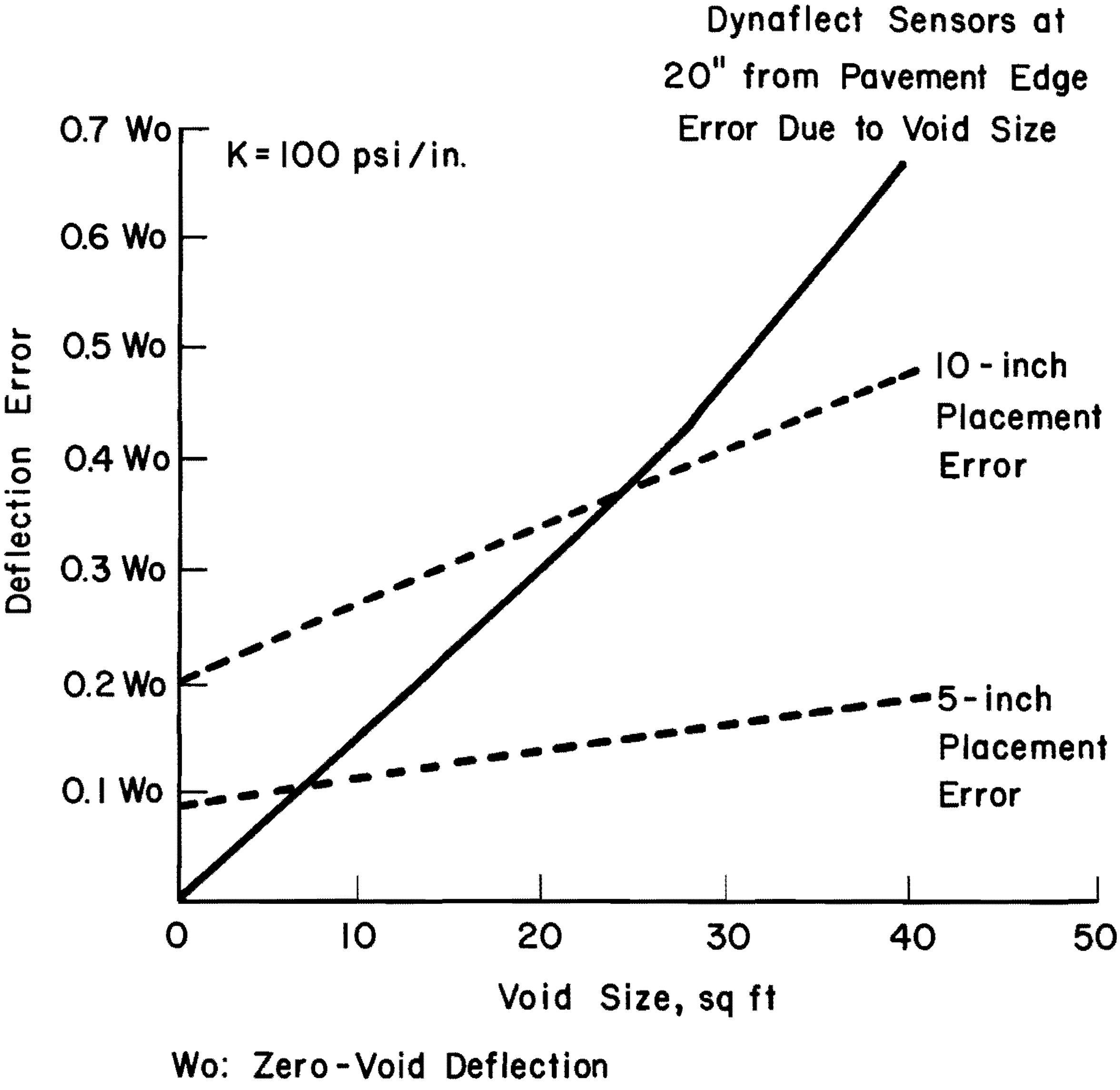


Fig 2.6. Deflection errors due to variations in Dynaflect placement as well as void size (Ref 5).

to determine reduction in the subgrade modulus if the depth to rigid bottom is known, as illustrated in Fig 2.7.

Consideration of rigid bottom in the basin fitting programs and estimating he depth to rigid bottom based on stress wave propagation theory have also been studied by Uddin et al (Ref 7) and are discussed in the next chapter.

Variation in Slab Thickness

The variation of thickness of the surface concrete layer is a source of error in deflections and it also influences the back-calculated Young's moduli. The error due to a variation in slab thickness has been investigated by Torres-Verdin and McCullough (Ref 5) in conjunction with the development of procedure to determine sample size for the Dynaflect deflection tests. From studies made in Ref 5, it is recommended that a change in slab thickness of ± 0.25 inch typically causes a variation of approximately 2.5 percent in the sensor 1 deflection.

SUMMARY

Investigations made to examine and quantify the effects of different factors that influence deflection measurements on rigid pavement have been reviewed in this chapter. These are summarized below.

(1) It is established that temperature differential significantly affects edge deflections indicating the need for temperature correction.

(2) The deflection data collected at different distances from the pavement edge should not be combined as they are significantly different from each other.

(3) Effects of void size and discontinuities on the Dynaflect deflections are also reviewed.

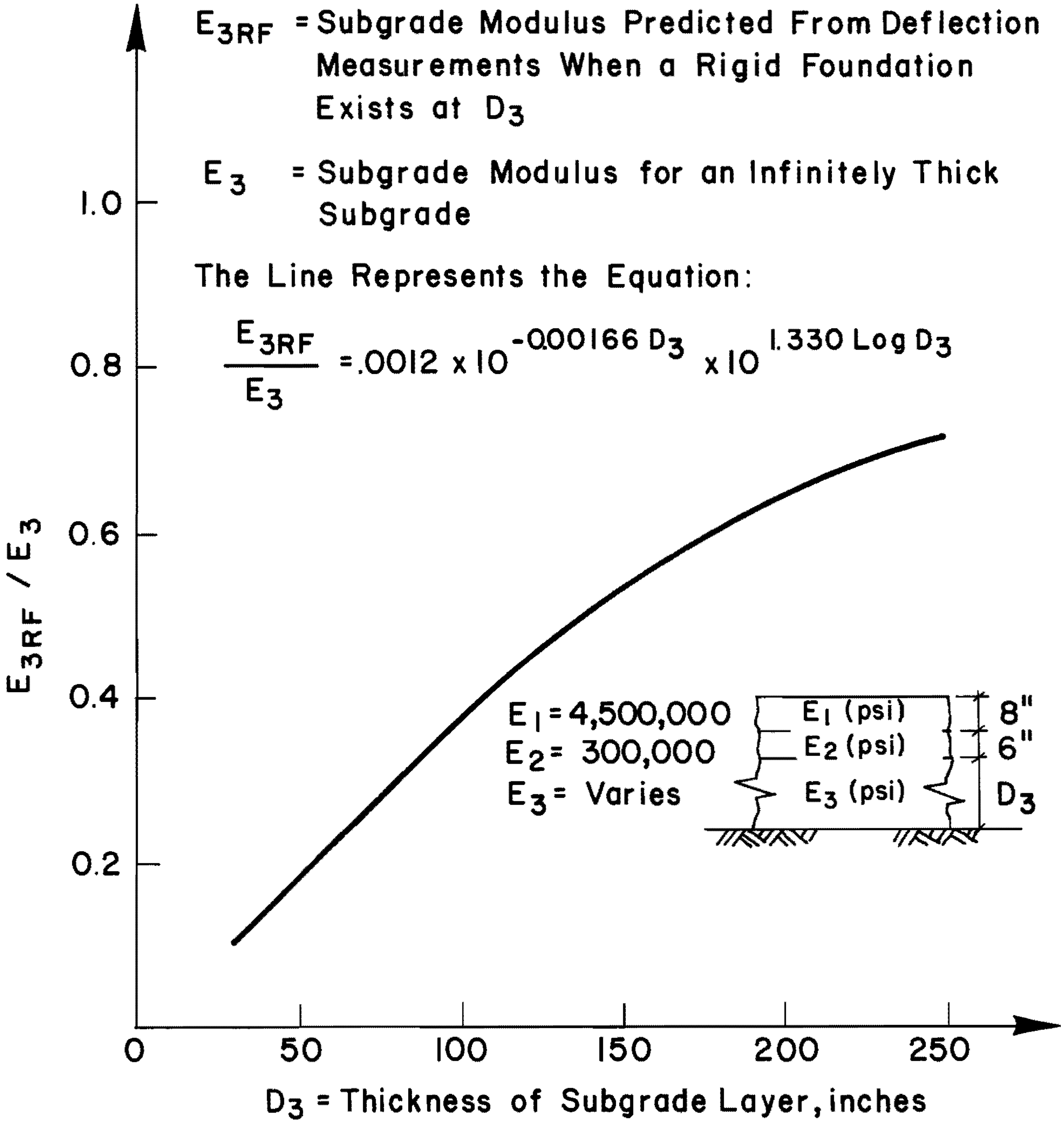


Fig 2. 7. The reduction in subgrade modulus predicted using deflection measurements when the subgrade is supported by a rigid foundation at depth D_3 (Ref 4).

(4) Different sources of errors in the deflections are reviewed and guidelines regarding the size of errors are also presented. These include

   (a) placement errors,
   (b) replication error,
   (c) error due to the presence of a rigid bottom of shallow depth, and
   (d) error due to variation in the thickness of the surface concrete layer.

CHAPTER 3. APPLICATIONS OF DYNAFLECT DEFLECTIONS

This chapter deals with several applications of Dynaflect deflections measurements for rigid pavement evaluation. The principal use of deflection measurements is to estimate the inplace structural adequacy of pavements. In combination with the condition survey data, deflections may be used for prioritization at the network level. The Dynaflect is then used extensively to evaluate the following for each design section.

(1) To calculate Young's moduli of subgrade and pavement layers which are also input in the overlay design procedure.
(2) Diagnostic checking for void detection and loss of load transfer across cracks and joints, using Dynaflect deflections.

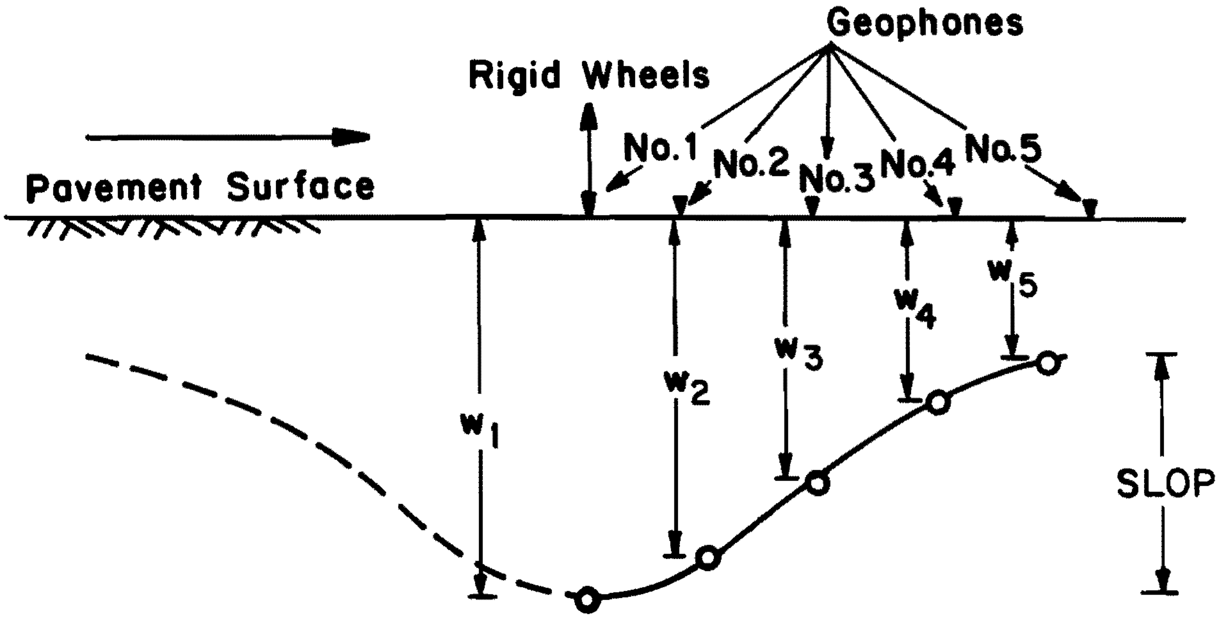
The following sections in this chapter present step-by-step procedures recommended for the use of Dynaflect deflections in four application areas--material characterization, void detection, load transfer evaluation, and reflection cracking analysis.

MATERIAL CHARACTERIZATION

Elastic layered theory is applied to analyze the Dynaflect deflections for material characterization. The procedure for analyzing the Dynaflect deflection basin for material characterization is based on work described in Ref 4.

Input Data

Deflection Data. The Dynaflect deflection basin (Fig 3.1) measured in the wheel path or near the center of slab and away from a transverse crack or joint (in the mid-span position) is to be utilized for material characterization.



Maximum Dynaflect Deflection = w_1

Basin Slope, SLOP = $w_1 - w_5$

Fig 3.1. Typical Dynaflect deflection basin.

Pavement Layers and Thickness Information. The number of pavement layers and their corresponding thicknesses are to be gathered from construction plans or from cores extracted as part of the evaluation program or the use of Spectral-Analysis-of-Surface-Waves method (Ref 16).

Initial Estimate of Material Properties of Pavement Layers. Initial estimates of Young's modulus and Poisson's ratio for each individual layer and subgrade are required at the start of the iterative basin fitting procedure. Typical values of Poisson's ratio for different pavement materials are given in Table 3.1. Theoretical deflections calculated from elastic layered theory are not appreciably affected by small deviations from the recommended values of Poisson's ratios.

The initial estimate of Young's modulus, E, for each pavement layer is to be obtained from any available information on laboratory test data or seismic tests, such as Spectrum-Analysis-of-Surface-Waves (SASW) tests (Ref 16). The practical range of Young's moduli, E, for typical pavement materials and natural soils is presented in Table 3.2. An indication of the type and extent of distress, based on the condition survey data and information on the age of the pavement, can be very helpful in selecting a reasonable value of E from Table 3.2. Surface concrete and base layers show a lesser degree of variation in E values than natural subgrade layers.

Basin Fitting Procedures

Computer Based Iterative Procedure. A rigid pavement structure can be modeled as a multi-layered linearly elastic system with homogeneous and isotropic material within each layer. The iterative procedure for back-calculation of Young's moduli is summarized below.

(1) Select a computer package based on layered theory, such as ELSYM5, LAYER15, or BISAR, for the calculation of the theoretical deflection basin.

(2) Determine data assumed to be known for input:
   (a) thickness information of each layer,
   (b) loading configuration of the Dynaflect, and

TABLE 3.1. POISSON'S RATIOS OF PAVEMENT MATERIAL

Material	Recommended Value	Observed Range[1]
P. C. Concrete	0.15	0.10 - 0.25
Cement stabilized base material	0.20	
Granular base (unbound)	0.40	0.20 - 0.50
Asphalt concrete	0.35	0.25 - 50
Subgrade Soil	0.40	0.5 (cohesive soil) 0.3 (non-cohesive soil)
Lime-treated subgrade	0.40	-

[1] (After Ref 12)

TABLE 3.2. YOUNG'S MODULUS OF ELASTICITY OF PAVEMENT MATERIALS

Materials	Typical Range of Young's Moduli, E
P. C. Concrete	$3 \times 10^6 - 6 \times 10^6$ *
Asphalt concrete	$0.2 \times 10^6 - 1.1 \times 10^6$ *
Cement-stabilized base	$0.5 \times 10^5 - 20 \times 10^5$ *
Unbound granular base (M_R)	
(a) Low confining pressure (5 psi)	$15 \times 10^3 - 35 \times 10^3$ *
(b) High confining pressure (50 psi)	$6 \times 10^4 - 11 \times 10^4$ *
Subgrade soils (M_R)	
(a) Cohesive clay type	$3 \times 10^3 - 4 \times 10^3$ *
(b) Fine grained sandy soil	$25 \times 10^3 - 30 \times 10^3$ *
Lime-treated subgrade	$5 \times 10^4 - 30 \times 10^4$ *

*(After Ref 12)

   (c) points on the surface and their offsets from the load where deflections are measured (Fig 1.2).

(3) Assign a reasonable estimate of Poisson's ratio and Young's modulus for each layer for the initial input.

(4) Determine the only output needed from the program, an array of surface deflections calculated on the relative positions of the five geophones.

(5) Compare the computed deflections with the measured insitu deflection basin. Once these are within a reasonable closure tolerance, 2 percent, the assumed values of Young's moduli become the final values.

(6) Otherwise go to step 3 and change the previous value of the modulus for one or more layers and continue the iterative procedure until a best fit to the measured deflection basin is achieved.

(7) Record the final combination of Young's moduli as the insitu moduli.

(8) This procedure is used to estimate Young's moduli for each deflection basin.

The following limitations should be recognized in the procedure of material characterization using the basin fitting technique:

(1) This iterative procedure does not give a unique solution, and therefore the final moduli should be checked to be within a reasonable range, as indicated in Table 3.2.

(2) Consideration should be given to the possibility of the existence of rigid bottom which is discussed later.

The measured and calculated (the best fit) deflection basins should be plotted to ensure that there are not shape breaks especially in the initial portion of the basin near sensor 1. The shape of the fitted basin can be improved only by adjusting the moduli. The results of a parametric study on a rigid pavement (Ref 7) can be used to improve the iterative procedure for calculating Young's moduli as summarized below.

(1) Change in the modulus of the subgrade layer causes the largest change in all deflection values,

(2) A corresponding change in the surface concrete layer results in relatively fewer changes in all deflection values, and change in sensor 5 deflection is less than half of the change in sensor 1 deflection.

(3) The deflection basin is least sensitive to changes in the moduli of the intermediate layers.

Graphical Procedure. An approximate procedure has been developed in Ref 4, based on a large number of elastic layered theory computations. The following conclusions were drawn from these computations:

(1) The subgrade modulus can be predicted with reasonable accuracy from sensor 5 deflection, and

(2) Basin slope (Fig 3.1) is not appreciably affected by changes in the modulus of subgrade and therefore the basin slope or (sensor 1-sensor 5) deflection can be used to estimate moduli of pavement layers.

The step-by-step procedure is outlined as follows:

(1) Estimate the subgrade modulus using sensor 5 deflection and thickness of concrete, from Fig 3.2.

(2) Use basin slope and subgrade modulus to estimate pavement layer moduli using the nomograph shown in Fig 3.3. This is an iterative procedure.

    (a) Use slope (W_1-W_5) from measured deflection basin and estimate of E_1 to find the turning point on line number 3.

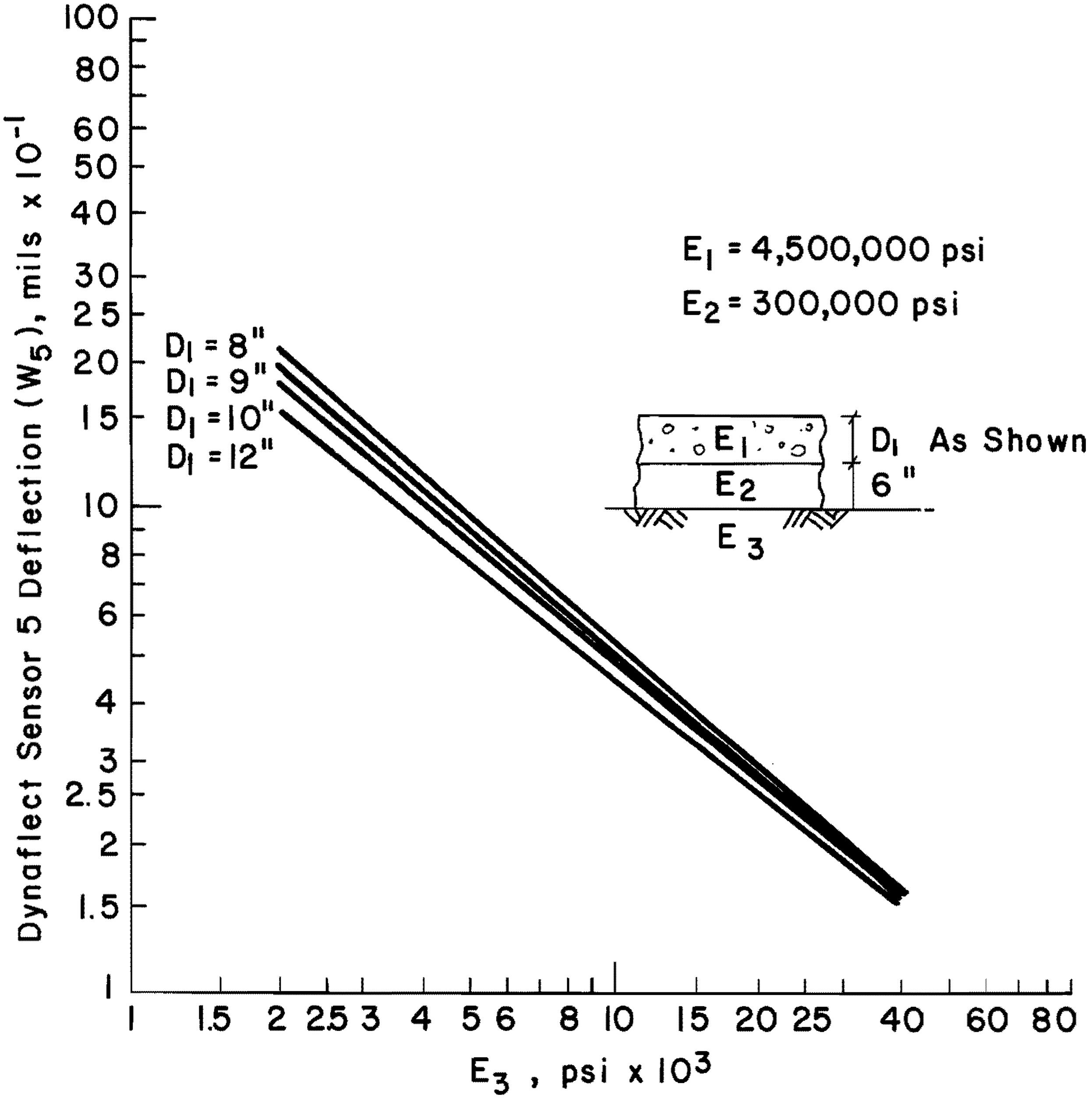


Fig 3.2. Dynaflect sensor 5 - subgrade modulus relationship for different rigid pavement thicknesses (Ref 4).

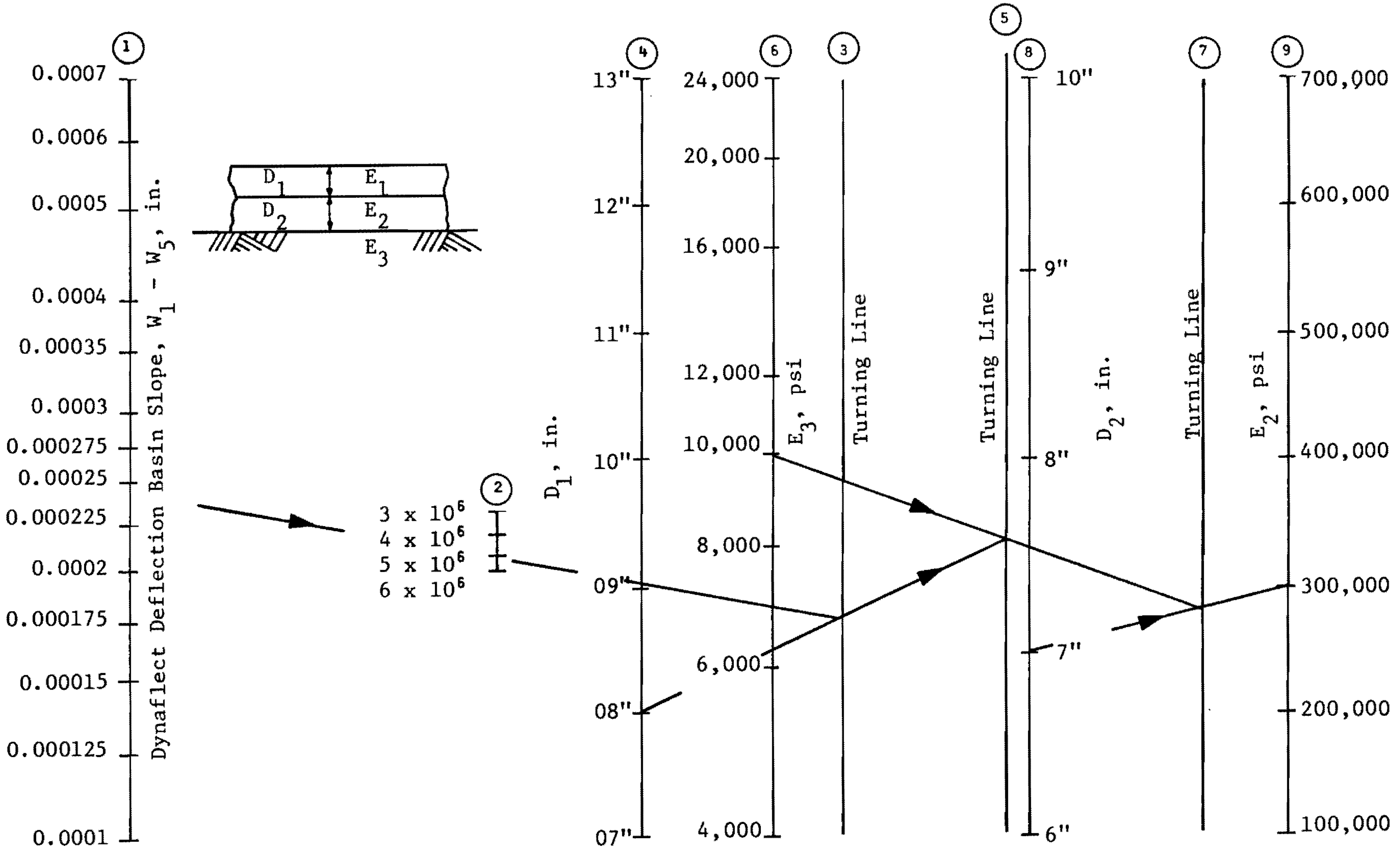


Fig 3.3. Nomograph for estimating subbase modulus of elasticity (E_2) for rigid pavements from Dynaflect deflections (Ref 23).

(b) Use this turning point and the value of slab thickness, D, on line 4 to locate the next turning point on line number 5.

(c) Locate the subgrade modulus value, E (determined from step 1) on line 6; connect it with the turning point on line 5. Extend this line to the next turning line number 7.

(d) Use this turning point on line 7 and thickness of the intermediate layer D_2 on line number 8 to draw a line passing through these points and extend it to line number 9 and read the value, which will be an estimate of Young's modulus of the intermediate layer, E_2.

This procedure can be used to obtain initial estimates of layer moduli for the earlier computer based procedure, and also as a check on the computer's results, but is not recommended for use in a final design.

Consideration of Rigid Bottom

Correction for the Effect of a Rigid Layer at a Known Depth. Layered theory programs in general assume an infinite subgrade. A laboratory resilient modulus, M_R value is often used in the material characterization. Using this value in the elastic layered theory program will result in a larger deflection in the case in which a rigid bottom exists at some shallow depth. In order to match the computed deflections with the measured deflection basin, the subgrade modulus is adjusted. The required reduction in the subgrade modulus (determined for an infinite subgrade) can be obtained by using the known depth of the subgrade to the rigid bottom or using Fig 2.7.

Selection of the Depth to Rigid Bottom. If a computer based basin fitting procedure is employed for material characterization, it is still possible to consider a rigid layer. This condition can be simulated by assigning a very large and fixed value to Young's modulus (e.g., 10^{99} psi) at the bottom of a subgrade layer of a known finite thickness. The deflection basin fitting procedure can then be used in the similar way as described earlier.

In the case in which a very stiff bottom, e.g., bed rock, is present at some unknown depth the depth to the rigid layer must be selected. The theory of the propagation of stress wave in an elastic half space can be used as a rational approach. If the velocity of compression wave, P-wave (V_p) is known, then the wave length (L_p) can be determined by using the relationship

$$V_p = f \cdot L_p$$

where f is the frequency of Dynaflect (8 Hz). The thickness of the subgrade layer can then be assumed to vary between half and full wave length. If data on sub-soil classification in the test area are accessible, then Table 3.3 can be used to select the depth to the rigid bottom. However this approach is applicable only when it is certain that a rock stratum does not exist at a depth of 20 feet or less on the test site. If it is suspected that the rigid layer is at a depth of less than 20 feet, then it is necessary to either bore for the depth or use SASW method as described in Ref 16, to determine the depth to the rock layer.

Stress Sensitivity of Subgrade

The subgrade value estimated from deflection basin can be adjusted for stress sensitivity of subgrade when considered critical by (1) determining M_R on cores at different stress levels (Ref 4) or (2) use of an NDT technique that allows variable load.

VOID DETECTION

Use of Deflection Measurements

Dynaflect deflections provide a fast and reliable means for detecting voids under rigid pavement and also for judging the effectiveness of any grouting operation for corrective maintenance. Birkhoff and McCullough (Ref

TABLE 3.3. ESTIMATION OF DEPTH TO RIGID BOTTOM (D_{SG})

Soil Type	Compression Wave* (P-Wave) Velocity V_p, ft/sec.	Suggested Thickness** of Subgrade D_{SG}, ft.
A. Unsaturated Condition		
Very Soft		
	800	50
Soft		
	1200	75
Medium		
	1800	≈ 113
Stiff		
Very Stiff	≈ 2500 ≈	≈ 156
B. Saturated Condition	≈ 5000 ≈	≈ 313

* Typical values of V_p, compression wave velocity are based on recommendations by Dr. K.H. Stokoe II, Professor of Soil Dynamics at The University of Texas at Austin.

** Depth of subgrade over the rigid bottom, D_{SG} is based on half wavelength corresponding to P-wave at 8 Hz.

2) have recommended two methods for using the Dynaflect deflection data to identify the areas likely to have voids. These methods involve (1) deflection basins and (2) W1 deflection profiles. The Dynaflect data are collected along the roadway. Two sets of deflection measurements are taken in each test section, one in the outside lane at 3 feet from the outside edge and the other at 3 feet from the center of the inside lane. This procedure has been revised (Ref 6) and is described later in this chapter.

Deflection Basin Method. The deflection basins at each station are plotted using Texas SDHPT computer program STCOE 1 (Ref 2). In the first method, the basin plots (Fig 3.4) are compared on a relative basis to determine the areas where high and deep basins exist, which indicate presence of voids.

Sensor 1 Deflection Profiles. In the second method deflection profile plots are produced based on maximum (sensor 1) deflection. This method is more efficient than the first method. The interior and edge deflection profiles (see Fig 3.5) are again compared on a relative basis.

The experimental Dynaflect data (Ref 7) and theoretical investigations on the effects of void size (Ref 5), and recent studies (Ref 6) as discussed in Chapter 2 have resulted in minor modifications to the procedure presented in Ref 2.

Recommended Procedure. Use of only sensor 1 deflections for plotting deflection profiles is preferred. The step-by-step procedure for analyzing the deflection data for void detection is presented in the following.

(1) Obtain the outside lane deflections at one foot from the pavement outside edge. The sensor 1 deflections are to be corrected for zero temperature differential condition.

(2) Obtain the outside lane deflection at center line. If the deflection measurements are also being made for material characterization at the center of the outside lane then this data will be sufficient to provide relative comparison.

(3) Plots of the two deflection profiles are to be produced as illustrated in Fig 3.5.

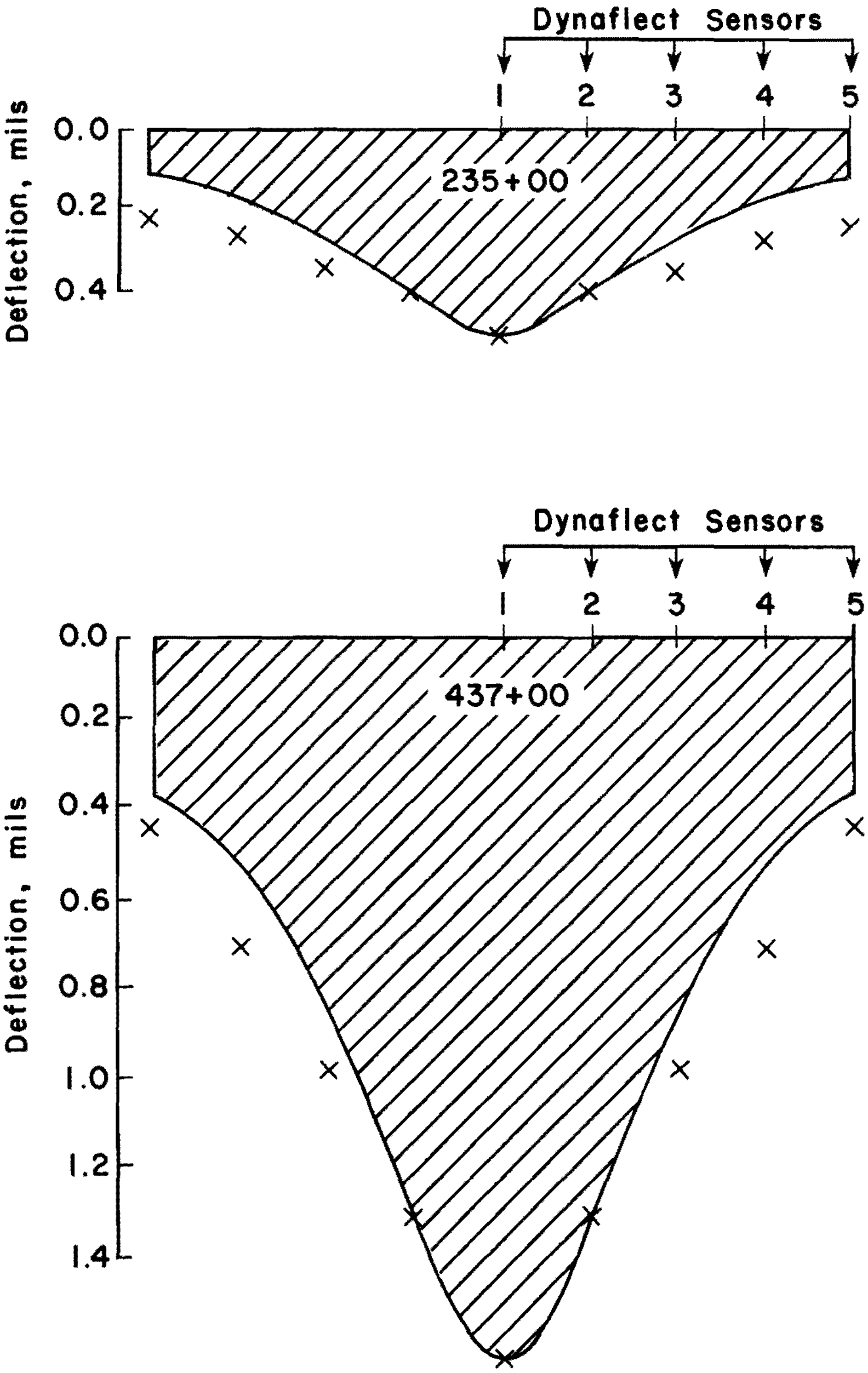


Fig 3.4. Comparison of high deflection and low deflection basins (Ref 2).

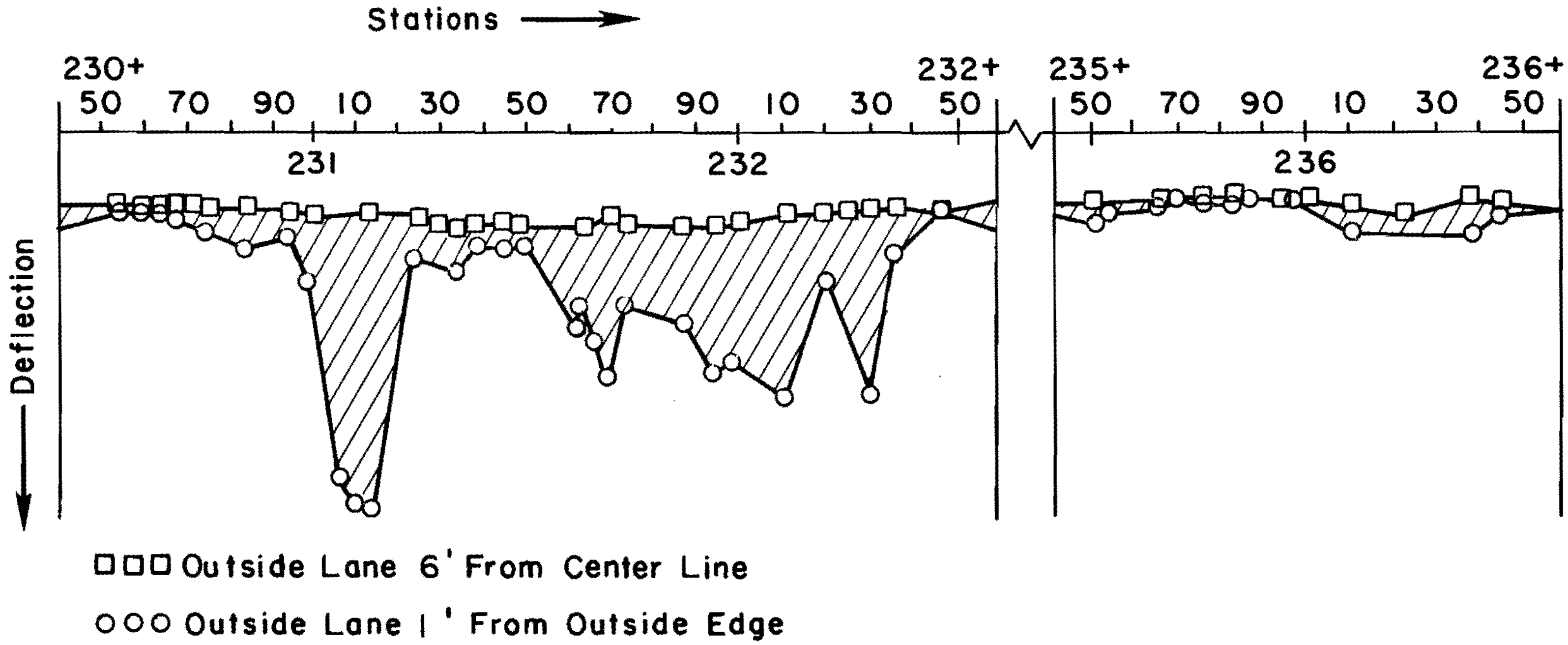


Fig 3.5. Example deflection profile for detection of voids.

(4) Areas susceptible to voids are to be marked on the plots on a relative basis, as illustrated in Fig 3.5.

Sources of Errors

Placement Error. The Dynaflect deflections can be significantly affected by the placement error, as discussed in Chapter 2. The Dynaflect loading wheels and sensor 1 should be as close to the marked position on the pavement as possible but no more than 5 inches out in any case.

Error Due to Temperature Differential. Temperature differential has a significant effect on Dynaflect edge deflections. In the early morning hours, a negative temperature differential will cause an increase in deflection. In the mid-afternoon when the maximum positive temperature differential occurs, observed deflections will be less than the corresponding deflections at zero temperature differential condition. Therefore, it is necessary to transform all edge deflections measured at different times of the day to the standard condition of zero temperature differential in the slab. An example of applying this correction is given in Ref 7.

Effectiveness of Grouting Operation

Dynaflect deflections are also used to evaluate the effectiveness of grouting operations to fill voids under the pavement. Practical examples are presented in Ref 6. A graphical procedure for this purpose has been developed in Ref 5. The step-by-step procedure is presented below.

(1) Obtain Dynaflect deflections after the undersealing operation at one foot from the outside edge in the outside lane.

(2) Apply temperature correction to sensor 1 deflections to correspond to zero temperature differential condition.

(3) Plot the corrected deflections before and after the grouting operation, as illustrated by dots in Fig 3.6. Also draw the equality line (solid line), which is at 45 degrees with respect to the abscissa.

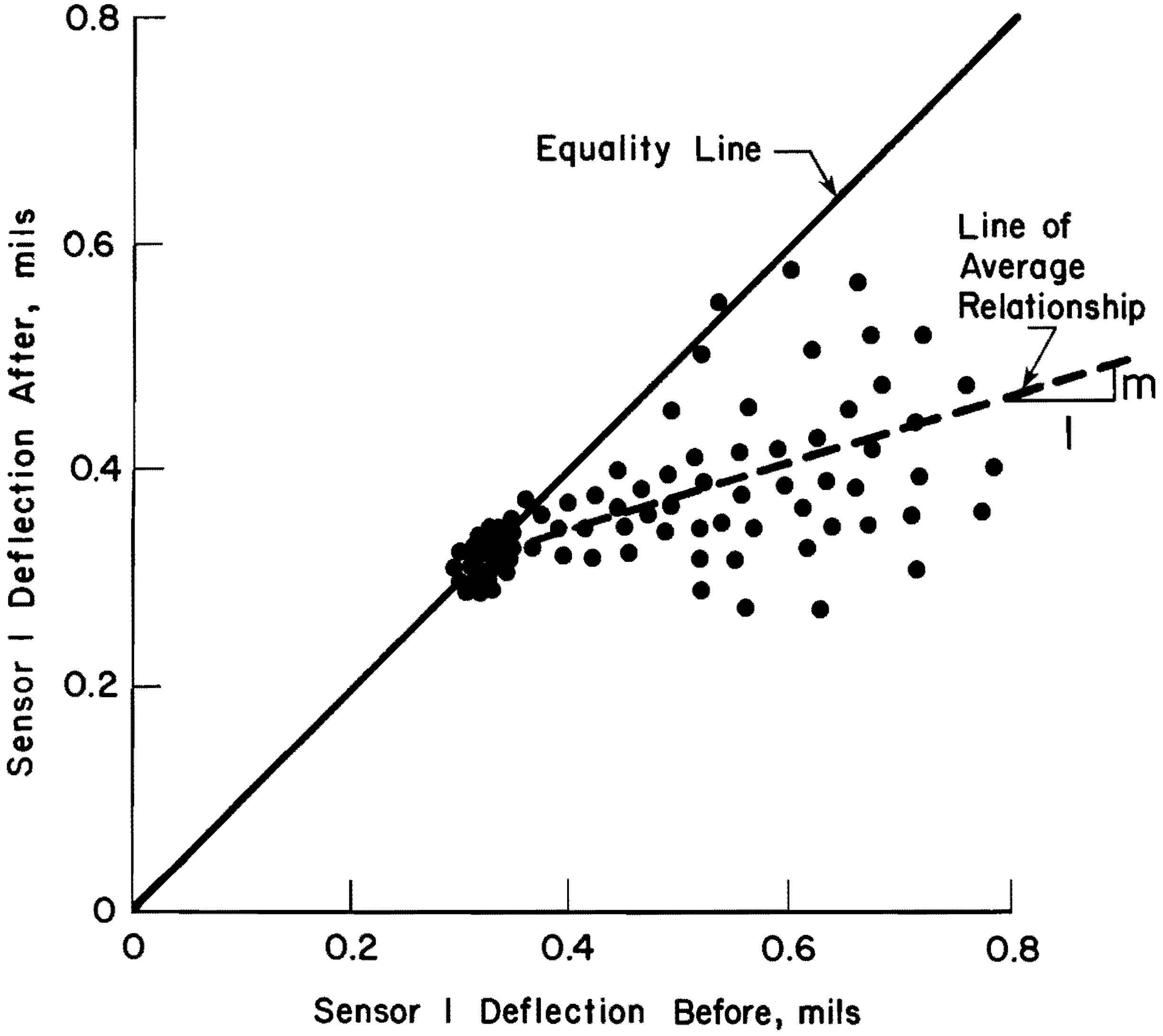


Fig 3.6. Example plot used in the recommended procedure for estimating the effectiveness of undersealing operations (Ref 5).

(4) Using a programmable calculator or a statistical package accessible at the Texas SDHPT computer, estimate a best fit simple linear regression line (dashed) having its origin in the area of greatest concentration of dots near the line of equality.

(5) Compare the estimated slope of the fitted line, m, with the values shown in Table 3.4 to estimate the effectiveness of the grouting operation.

LOAD TRANSFER EVALUATION

Background

The presence of discontinuities in the surface concrete layer is an important characteristic of rigid pavements. These discontinuities are (1) irregular transverse cracks in continuously reinforced concrete pavement, (2) controlled transverse cracking in sawed contraction joints in plain or reinforced jointed concrete pavement and (3) contraction or expansion joints where dowels are used for providing load transfer. The transverse cracks in CRC pavements and JRC pavements are held tight by reinforcement. In designing a new pavement, full load transfer across these discontinuities is always implied. However gradual deterioration of the discontinuities over the years caused by environmental changes and accumulation of traffic loads results in partial load transfer. A loss in load transfer is associated with an increase in deflection.

Mechanism of Load Transfer

Strauss et al (Ref 3) present discussions on the mechanisms of load transfer and theoretical models to estimate load transfer. For CRC pavement, three mechanisms of load transfer across cracks are discussed--through moment transfer, aggregate interlock, and dowel action of steel reinforcement. Mathematical models are developed for the three cases and compared with the field data. It is concluded that (1) the probability of moment transfer at a crack is very small unless crack width is very narrow which is possible only

TABLE 3.4. PERCENT OF VOID AREA FILLED AS A FUNCTION OF SLOPE, m

m	Percent of Void Area Filled
1.0	0
0.8	20
0.6	40
0.4	60
0.2	80
0.0	100

for new pavements; (2) and the burden of the load transfer has to be carried by aggregate interlock and dowel action of the longitudinal steel reinforcement.

Use of the Dynaflect Deflections

Analytical Investigations. A crack in a rigid pavement can be simulated by reducing the slab bending stiffness in the SLAB49 computer model (Ref 17). It can be assumed that the load transfer at a transverse crack is a function of the percentage reduction in the slab bending stiffness along the crack. This assumption makes it convenient to use deflection measurements to estimate loss in load transfer.

Numerous SLAB49 computer runs were made to develop a dimensionless chart for load transfer evaluation. The CRC pavement structure assumed in the study is 10 inches surface concrete layer ($E = 4 \times 10^6$ psi, Poisson's ratio = 0.15) over a stabilized base with K on top equal to 800 pci. Average crack spacing is assumed to be 8 feet. A 9-kip wheel load is applied at 5 feet from the outside edge of the outside lane and computations are made at different levels of reduction in slab bending stiffness to calculate (1) deflections d_i when the load is applied in between cracks and (2) deflections d_c when the load is applied at the crack.

Estimation of Loss in Load Transfer. Figure 3.7 illustrates a curve on a dimensionless plot developed from the results of the analytical study (also valid for K_{top} of 2000 pci). The curve represents a relationship between deflection ratio (DR) and load transfer factor (LTF) which are defined below.

$$DR = d_c/d_i \tag{3.1}$$

where d_c and d_i are deflections at the crack and in the mid span position, respectively.

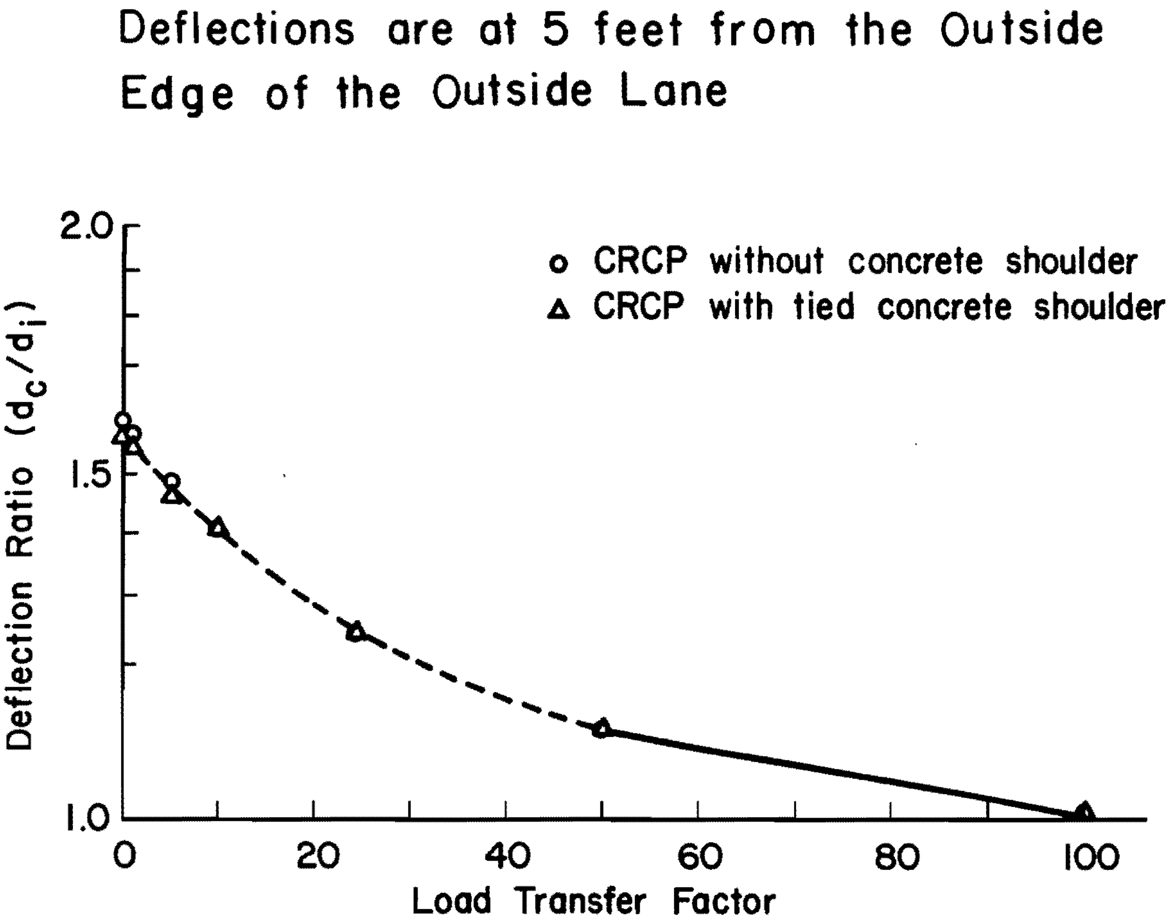


Fig 3.7. Log (d_c/d_i) versus load transfer factor CRCP.

$$\text{LTF} = 100 - \text{percent reduction in slab bending stiffness} \qquad (3.2)$$

The relationship shown in Fig 3.7 is unique for CRC pavements with and without tied concrete shoulder. Assumption of linearity in the theoretical model used for computations validates use of the Dynaflect deflection measurements to obtain deflection ratio d_c/d_i and estimate the corresponding load transfer using Fig 3.7. The same figure can also be used for evaluation of contraction or warping joints in JRC pavements.

Application of the Developed Procedure

The dimensionless curve in Fig 3.7 has been used to evaluate loss in load transfer using the Dynaflect data collected at Columbus, Texas, (Ref 7). Deflection ratios, d_c/d_i, of 1.06 or lower are observed for the fall data of sensor 1 deflections measured in the wheel path, which is typical of a new CRC pavement. This corresponds to an LTF equal to or more than 70 percent.

REFLECTION CRACKING ANALYSIS

Background

A recent study has been carried out by Mendoza and McCullough (Ref 23) to develop design charts for use in the design of hot mix asphalt concrete (HMAC) overlays on portland cement concrete (PCC) pavements to prevent reflection cracking. Reference 24 is the source for a detailed theoretical treatment of the reflection cracking analysis procedure.

Procedure of Dynaflect Testing

An important step in the reflection cracking analysis procedure is to make field deflection measurements prior to overlay placement on a number of joints or cracks in a given design section by loading on one side of each joint (or crack) and measuring the deflections on both loaded and unloaded sides. The Dynaflect device may be used for these measurements. The deflection factor for each joint, F_w, can be computed as:

$$F_w = \frac{w_l - w_u}{w_l + w_u} \qquad (3.3)$$

where

w_l = deflection on loaded side, and
w_u = deflection on unloaded side.

Figures 3.8 and 3.9 show the location of the Dynaflect load and geophones in order to determine the required deflection values.

Application

References 23 and 24 present the concept that the maximum shear strain, $_{OV}$ to which an overlay can be subjected is expressed as

$$\gamma_{OV} = f\left[N_T, \text{EDV}\right] \qquad (3.4)$$

where

N_t = repetitions of design 18-kip single axle load, and
EDV = dynamic modulus of elasticity of the overlay material.

Next, an impression is obtained for the maximum allowable deflection factor, F_w

$$F_w = f\left[\gamma_{OV}, \text{EDV}, \text{THOV}, \text{ED2}, \text{TH2}\right] \qquad (3.5)$$

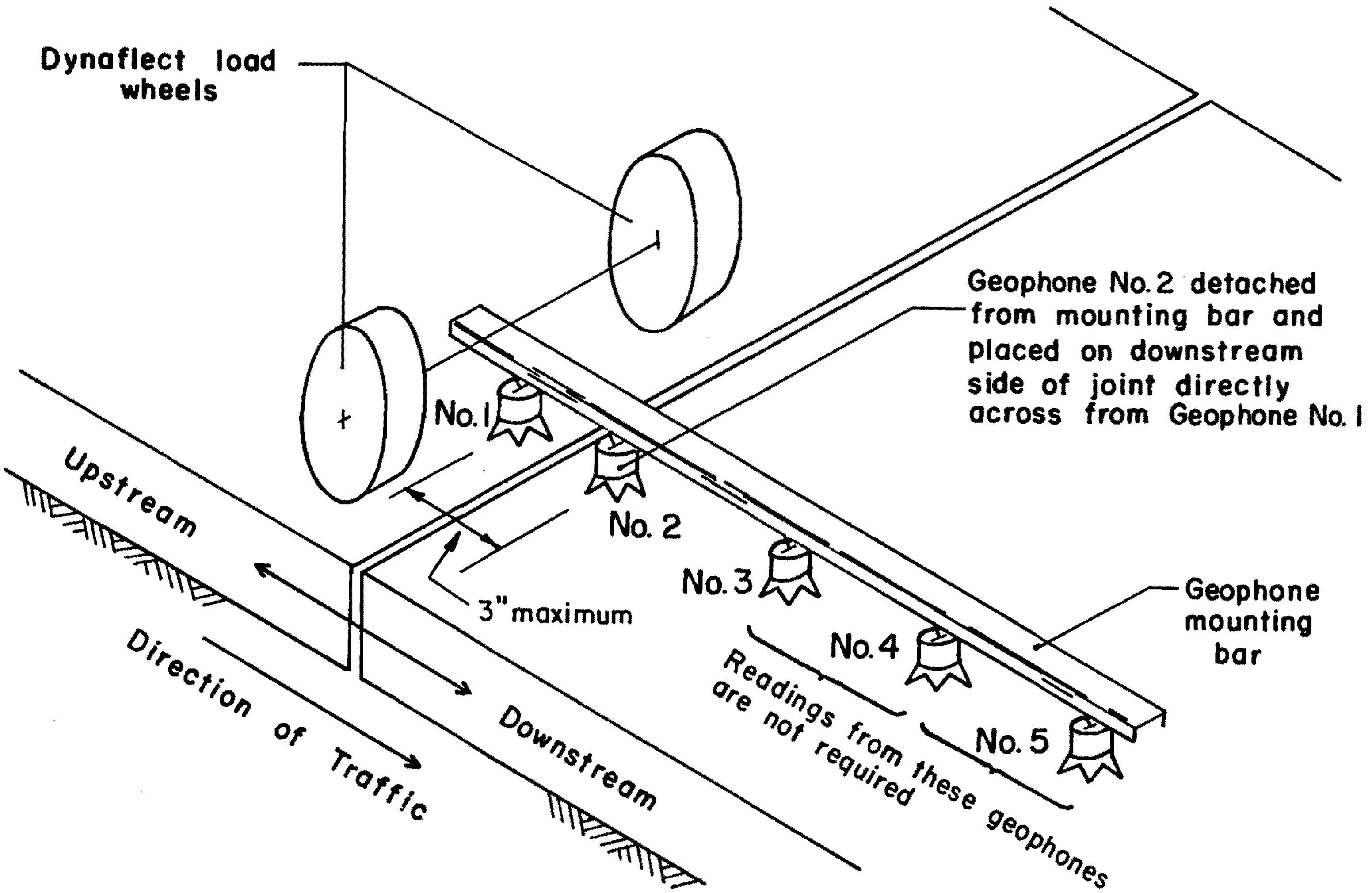


Fig 3.8. Required positioning of Dynaflect load wheels and geophones for load transfer deflection measurements (after Ref 24).

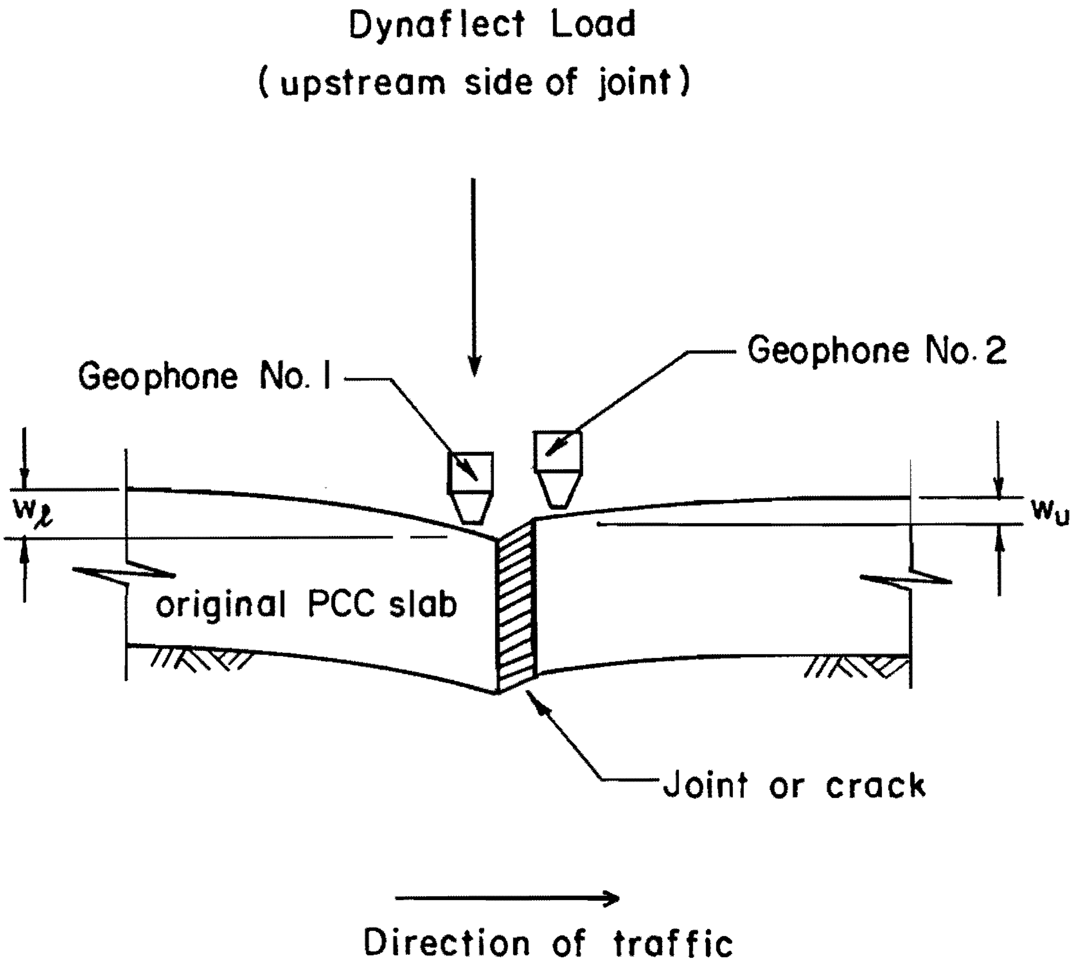


Fig 3.9. Illustration of Dynaflect deflection load and geophone configuration for determining required deflection values (after Ref 24).

where

THOV = overlay thickness, inches,

ED2 = dynamic modulus of the intermediate layer,

TH2 = thickness of intermediate layer, and

γ_{OV} and EDV are defined earlier.

Based on the relations 3.4 and 3.5, a graphic procedure has been prepared by Mendoza and McCullough (Ref 24) to determine the critical deflection factor as illustrated in Fig 3.10. This chart is applicable to the six composite climatic zones of Texas as shown in Fig 3.11. The critical value of deflection factor obtained from Fig 3.10 must not be exceeded by the actual deflection factors of each joint (or crack) obtained from the field deflection measurements for the particular section being designed. Those joints (or cracks) whose deflection factors exceed the maximum deflection factor should be subjected to an appropriate measure of rehabilitation before overlay placement so that premature reflection cracking will be avoided (see Fig 3.12).

SUMMARY

The three major applications of the Dynaflect deflections as related to rigid pavement evaluation have been presented in this chapter. Detailed guidelines are included on insitu material characterization of pavement materials using Dynaflect deflections. Step-by-step procedures for detecting voids beneath rigid pavements and evaluating the effectiveness of grouting operations are described. A brief background on load transfer evaluation and specific recommendations on using the Dynaflect deflections to estimate loss in load transfer and diagnostic checking of the cracks or contraction joints are also presented. Use of Dynaflect deflections in reflection cracking analysis is also discussed.

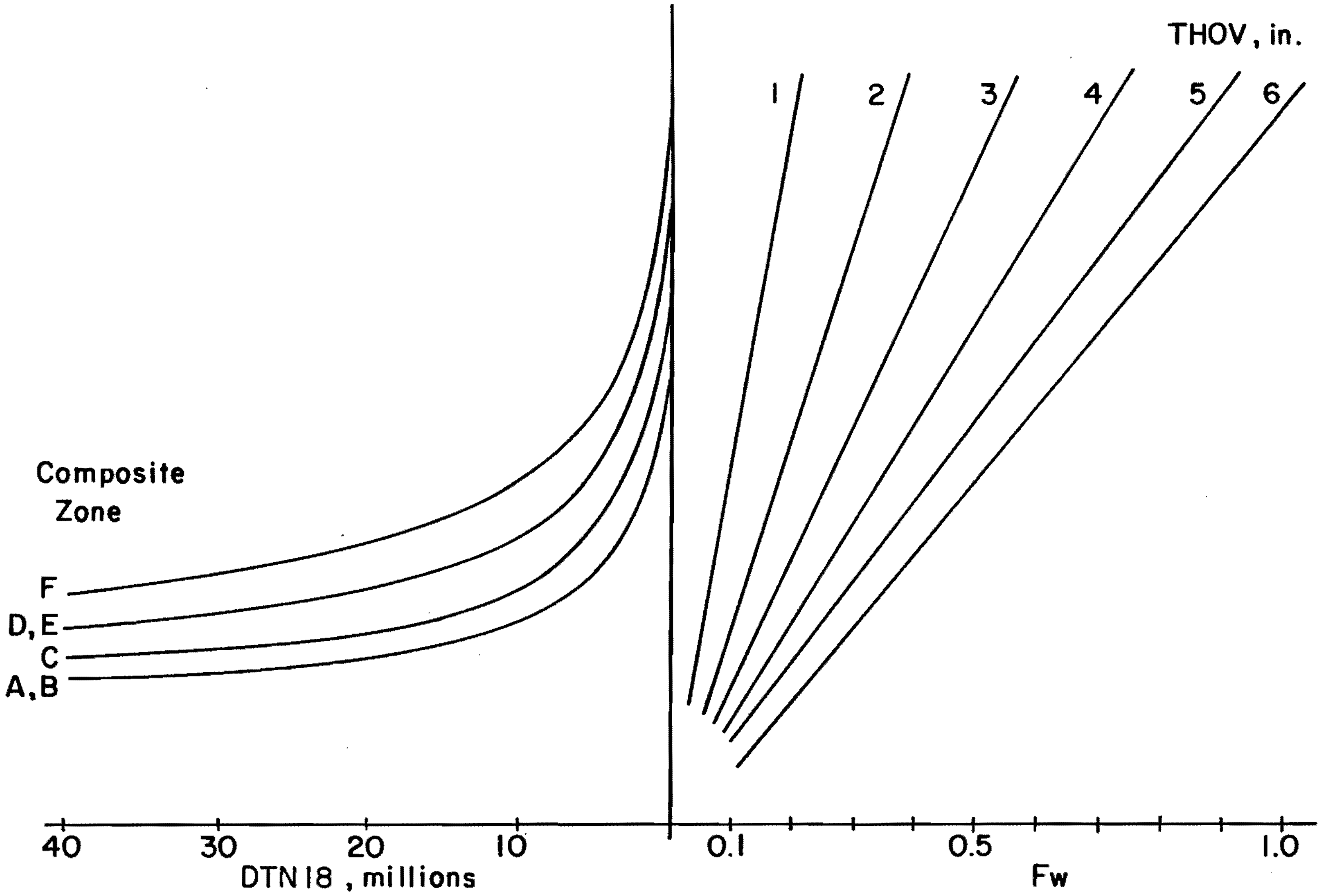
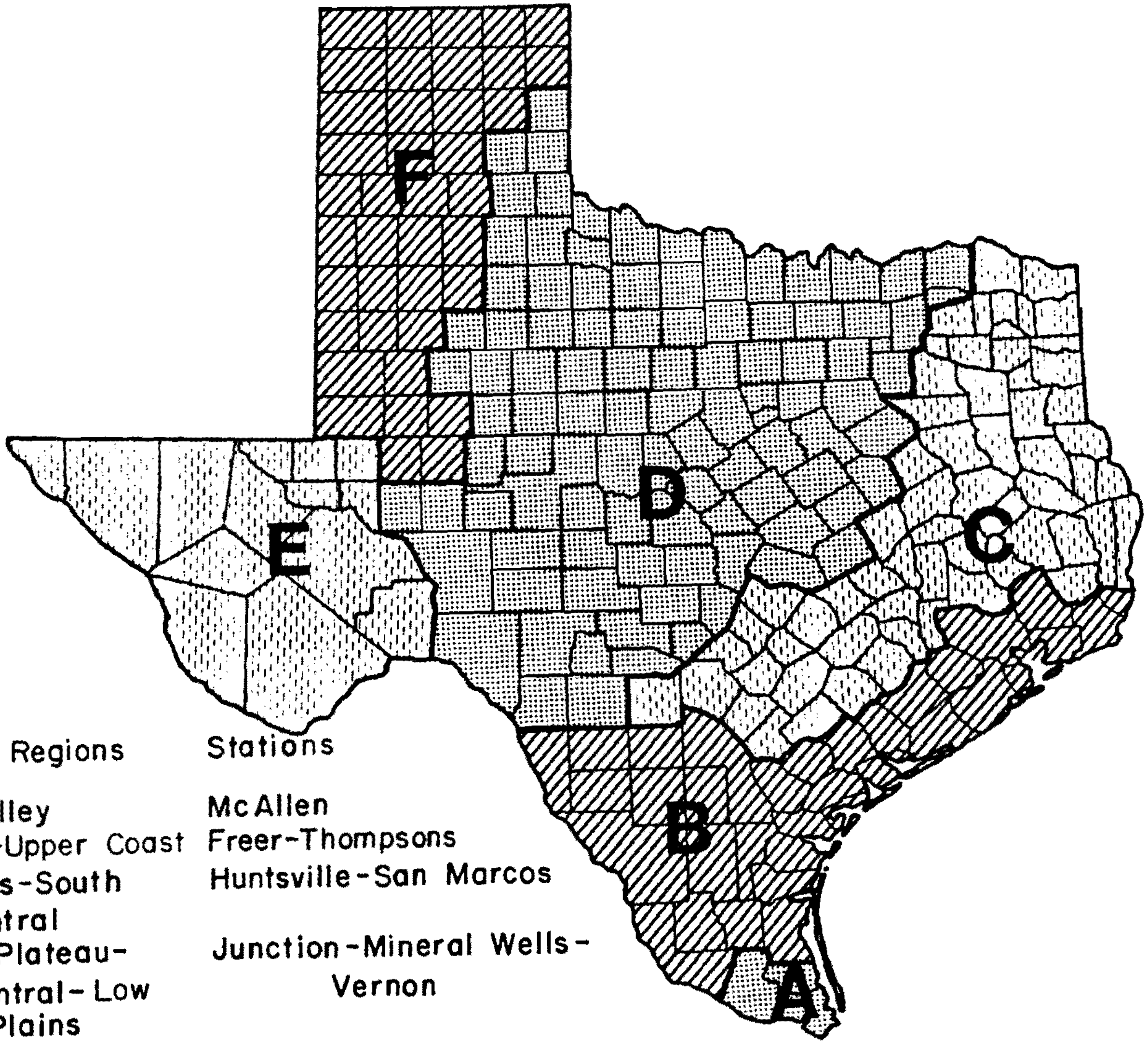


Fig 3.10. Design chart for estimating allowable deflection factor, F_w, (Ref 23).



Zones	Combined Regions	Stations
A	Lower Valley	McAllen
B	Southern-Upper Coast	Freer-Thompsons
C	East Texas-South Central	Huntsville-San Marcos
D	Edwards Plateau-North Central-Low Rolling Plains	Junction-Mineral Wells-Vernon
E	Trans Pecos	Fort Stockton
F	High Plains	Plainview

Fig 3.11. Six composite zones.

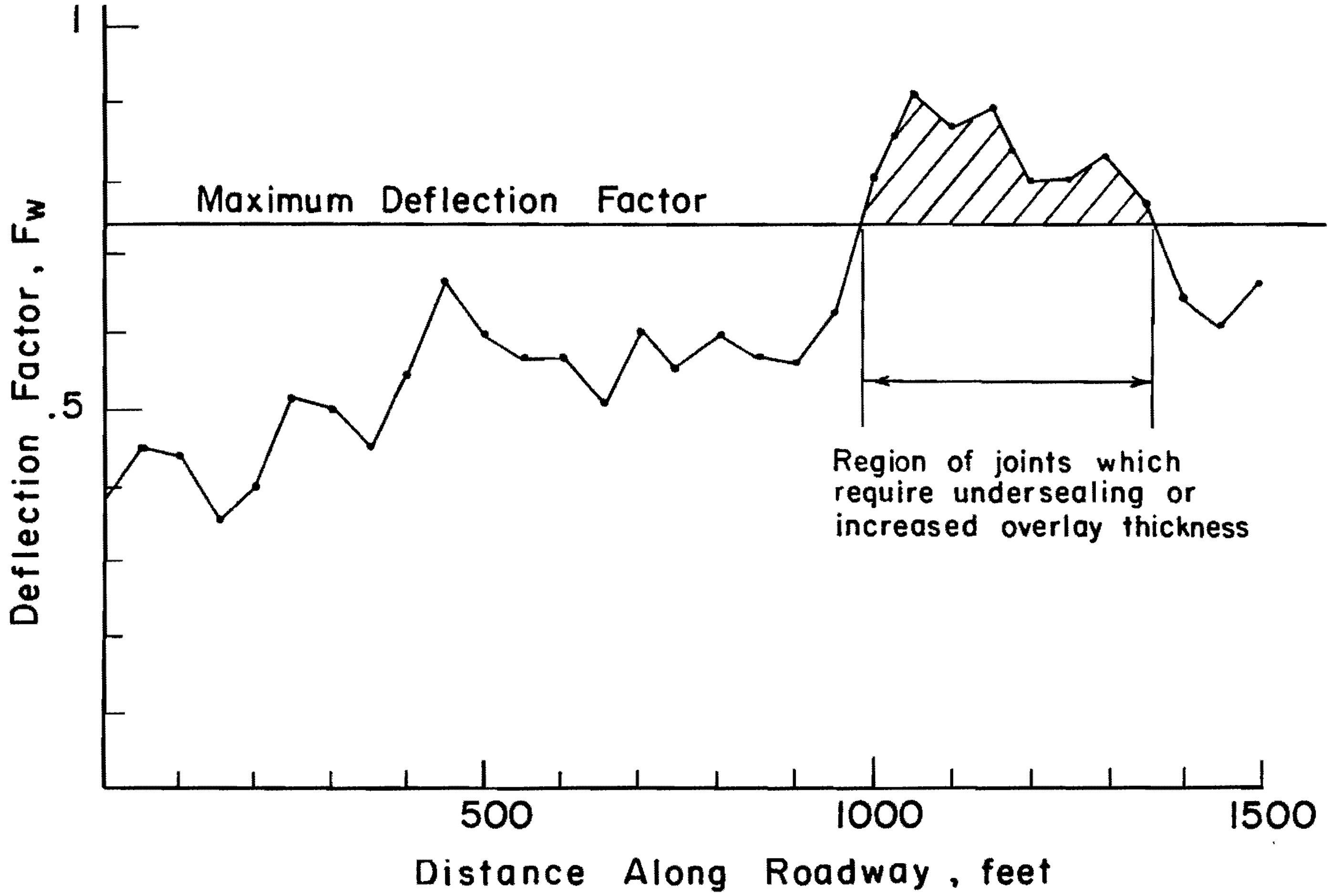


Fig 3.12. Graph of field deflection factors for 50-foot JCP illustrating application of maximum deflection factor in detecting joints which will cause premature reflection cracking in the overlay design considered (after Ref 24).

Temperature correction is required in the case of the Dynaflect sensor 1 deflections measured at one foot from the pavement edge for the purpose of void detection. This necessitates measurement of temperature both at top and bottom of the concrete slab. As an alternative, a simple procedure for predicting temperatures in a concrete slab using local climatological data is presented in the next chapter.

CHAPTER 4. ESTIMATION OF TEMPERATURE IN CONCRETE SLABS

Dynaflect deflection measurements made for the purpose of void detection must be corrected to remove the influence of temperature differential. This implies measurement of temperature at the top and bottom of the concrete slab simultaneously with the use of Dynaflect. This chapter describes an alternate procedure for estimating temperature in the concrete slab based on climatological data and thermal properties of concrete. The development of the temperature predictive model is described in detail in Ref 7.

INFORMATION REQUIRED TO ESTIMATE PAVEMENT TEMPERATURE

Different climatological information from daily weather report and material properties required to estimate temperature in concrete pavement are presented in this section.

Climatological Data

Ambient Air Temperature. The daily air temperature variations follow a sinusoidal function of time and the temperature is the most important factor to influence the surface temperature of a concrete pavement. The hourly record of air temperature is not maintained in all weather stations. Therefore, the model relies on daily maximum and minimum air temperatures which are always included in daily weather reports.

Solar Radiation. Solar radiation is also a major contributor to temperature changes in concrete pavement. The local weather stations report total solar radiation in Langleys per day. Solar radiation is affected by the cloud cover.

Wind Speed. Average wind speed is also an input in the model because it influences the surface temperature. Strong wind tends to decrease the surface temperature.

Thermal Properties of Concrete

Table 4.1 presents the thermal properties of concrete and typical values for pavement-quality concrete.

TEMPERATURE MODEL AND APPLICATION

Theoretic Model

The theoretical model described by Shahin and McCullough (Ref 18) has been revised by Uddin et al (Ref 7) for applicability to concrete pavements. The mathematical model is based on the theory of conduction of heat through a semi-infinite homogeneous mass. The final form of the model is described in Ref 7.

Computer Program and Application

Complete listing of the revised computer program PTEMP based on the theoretical model is given in Ref 7 with examples of input and output. A simplified flow chart of the program, is presented in Fig 4.1. Temperature parameters of the concrete slab at the CRC pavement, at Columbus, Texas, in August, 1981 have been estimated using computer program PTEMP. The climatological data thermal properties and the calculated hourly distribution of temperatures are given in the example output in Table 4.2. The estimated and measured temperature data are plotted in Fig 4.2 for comparison. Weather data were obtained from weather reports published by NOAA (Ref 19).

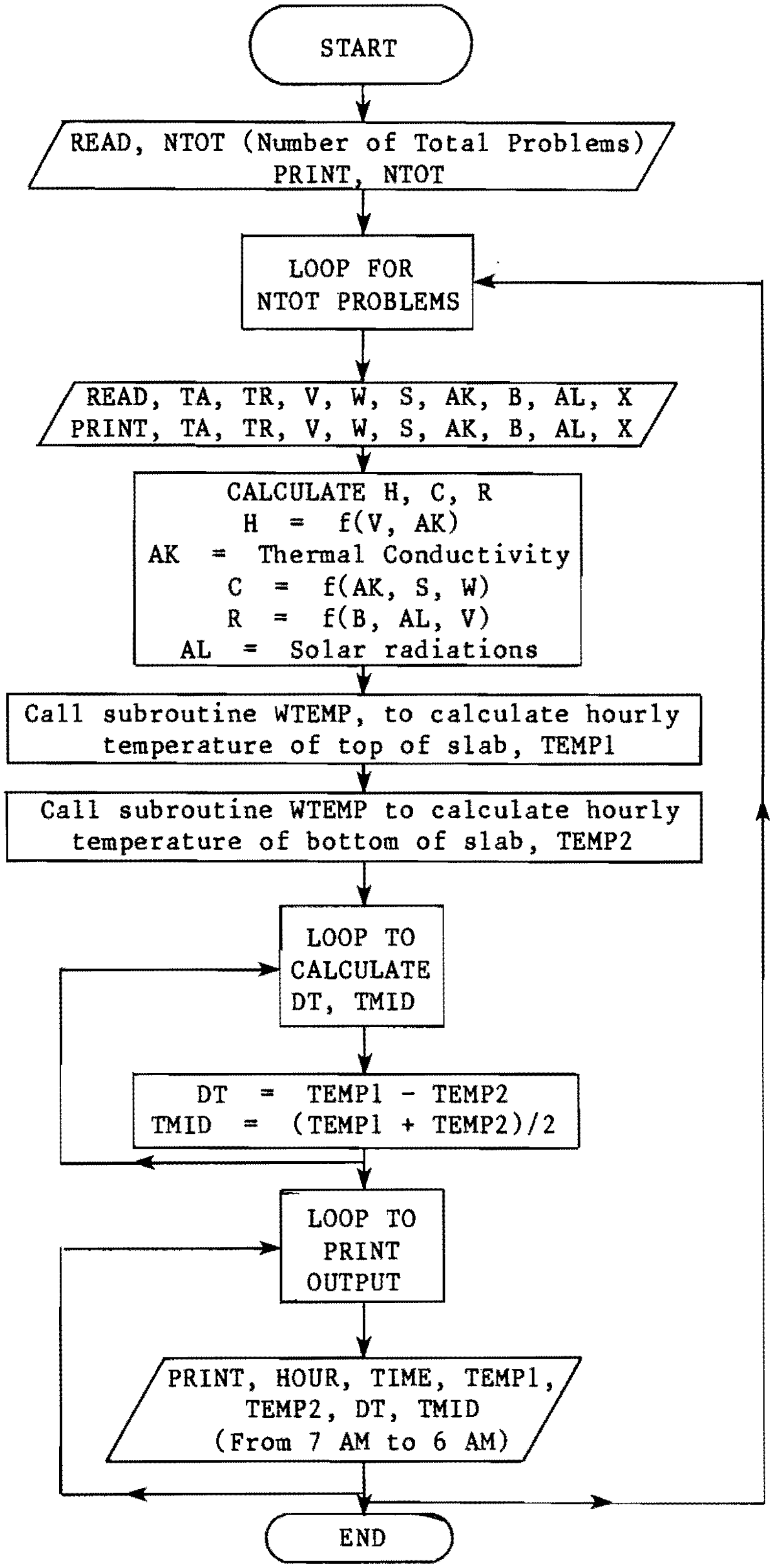
SUMMARY

A temperature predictive model has been described in this chapter for use in an alternate procedure if actual measurement of temperature in concrete pavement is not possible. Typical values for thermal properties of

TABLE 4.1. THERMAL PROPERTIES OF PAVEMENTS P.C. CONCRETE (REF 7)

Properties	Portland Cement Concrete	Asphalt Cement Concrete
Absorptivity of surface to solar radiation	0.65 - 0.80 (Ref 23)	0.95**
Thermal conductivity (BTU/ft^2/hr, °F)		0.7**
Aggregates:		
Gravel	0.9**	
Igneous	0.83*	
Dolomite/limestone	2.13*	
Specific heat (BTU/lb, °F)	0.20 - 0.28*	0.22**

* (Ref 35)
** (Ref 4)



(continued)

Fig 4.1. Simplified flow chart of temperature prediction program, "PTEMP."

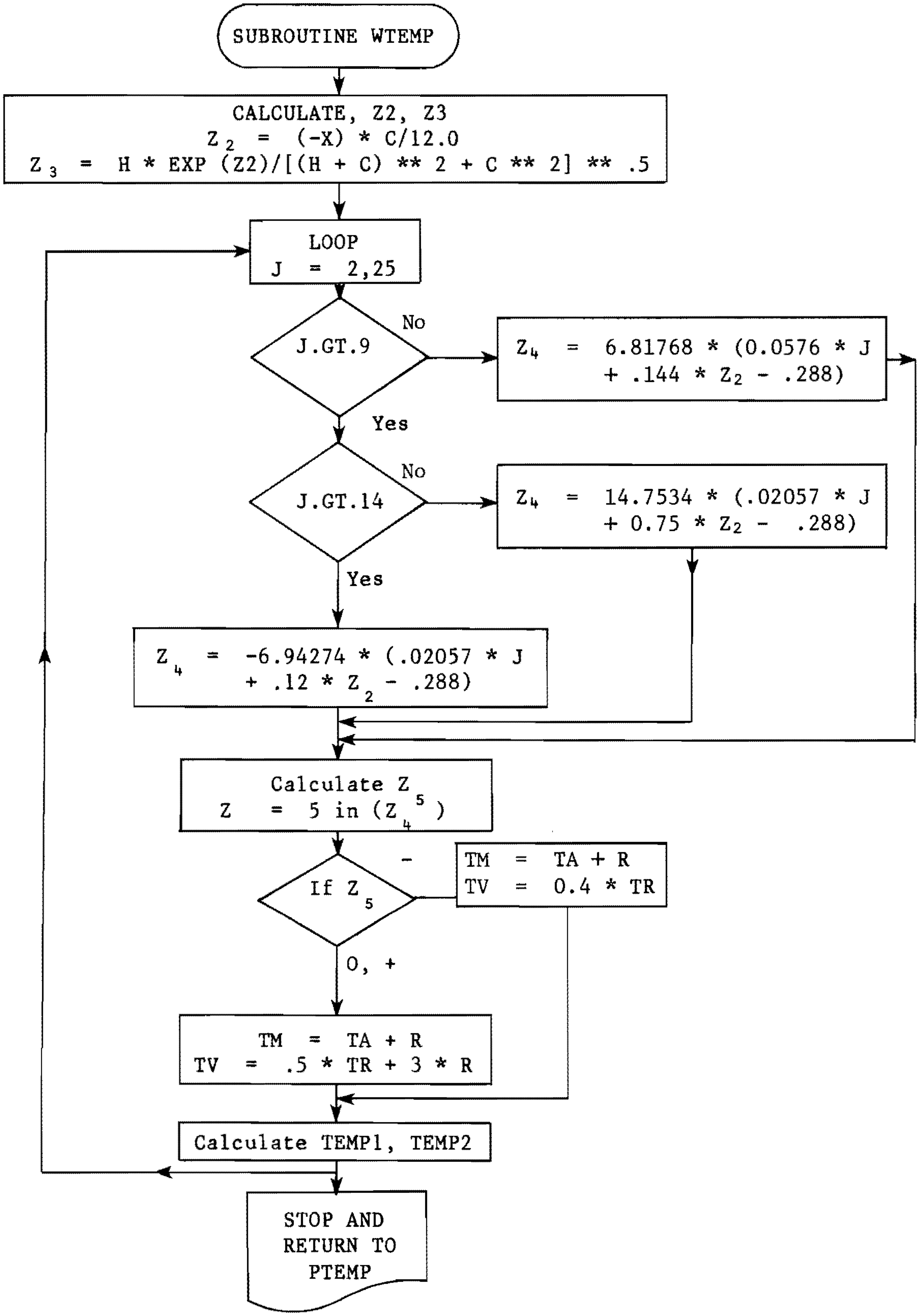


Fig 4.1. (continued)

TABLE 4.2. EXAMPLE OUTPUT

```
 PROB. NO.          1       COLUMBUS BYPASS SH 71  AUG.06,1981

AVE. AIR TEMP.=     85.500      DEG.F
TEMP.RANGE    =     25.000      DEG.F
WIND VELOCITY =      8.300      MPH.
MATL. DENSITY =    150.000      PCF.
SPECIFIC HEAT =       .240      BTU.PER POUND DEG.F
CONDUCTIVITY  =       .900      BTU.,HOUR,FT.,DEG.F
ABSORBTIVITY  =       .750
SOLAR RAD.    =    575.000      LANGLEYS PER DAY
DEPTH         =     10.000      INCHES


  HOUR OF DAY          TEMP,TOP   TEMP,BOTTOM     DT        TMID


HOURS                  DEG.-F      DEG.-F       DEG.-F     DEG.-F

  1      7  A.M.         89.8       95.6         -5.9       92.7
  2      8  A.M.         91.1       95.3         -4.1       93.2
  3      9  A.M.         93.2       95.0         -1.7       94.1
  4     10  A.M.         95.7       94.8           .9       95.3
  5     11  A.M.        106.4       94.8         11.6      100.6
  6     12  NOON        115.4       94.9         20.5      105.1
  7      1  P.M.        121.4       95.1         26.3      108.3
  8      2  P.M.        123.5       95.4         28.1      109.5
  9      3  P.M.        121.8       95.5         26.2      108.7
 10      4  P.M.        117.7       96.2         21.5      106.9
 11      5  P.M.        111.6       97.4         14.2      104.5
 12      6  P.M.        104.0       98.5          5.6      101.2
 13      7  P.M.         95.7       99.3         -3.5       97.5
 14      8  P.M.         94.8       99.8         -5.0       97.3
 15      9  P.M.         93.9       99.7         -5.8       96.8
 16     10  P.M.         93.0       99.5         -6.5       96.3
 17     11  P.M.         92.2       99.2         -7.0       95.7
 18     12  MIDNIGHT     91.5       98.9         -7.4       95.2
 19      1  A.M.         90.8       98.5         -7.6       94.7
 20      2  A.M.         90.3       98.0         -7.7       94.1
 21      3  A.M.         89.8       97.5         -7.7       93.7
 22      4  A.M.         89.5       96.9         -7.4       93.2
 23      5  A.M.         89.3       96.4         -7.0       92.8
 24      6  A.M.         89.3       95.8         -6.5       92.5
```

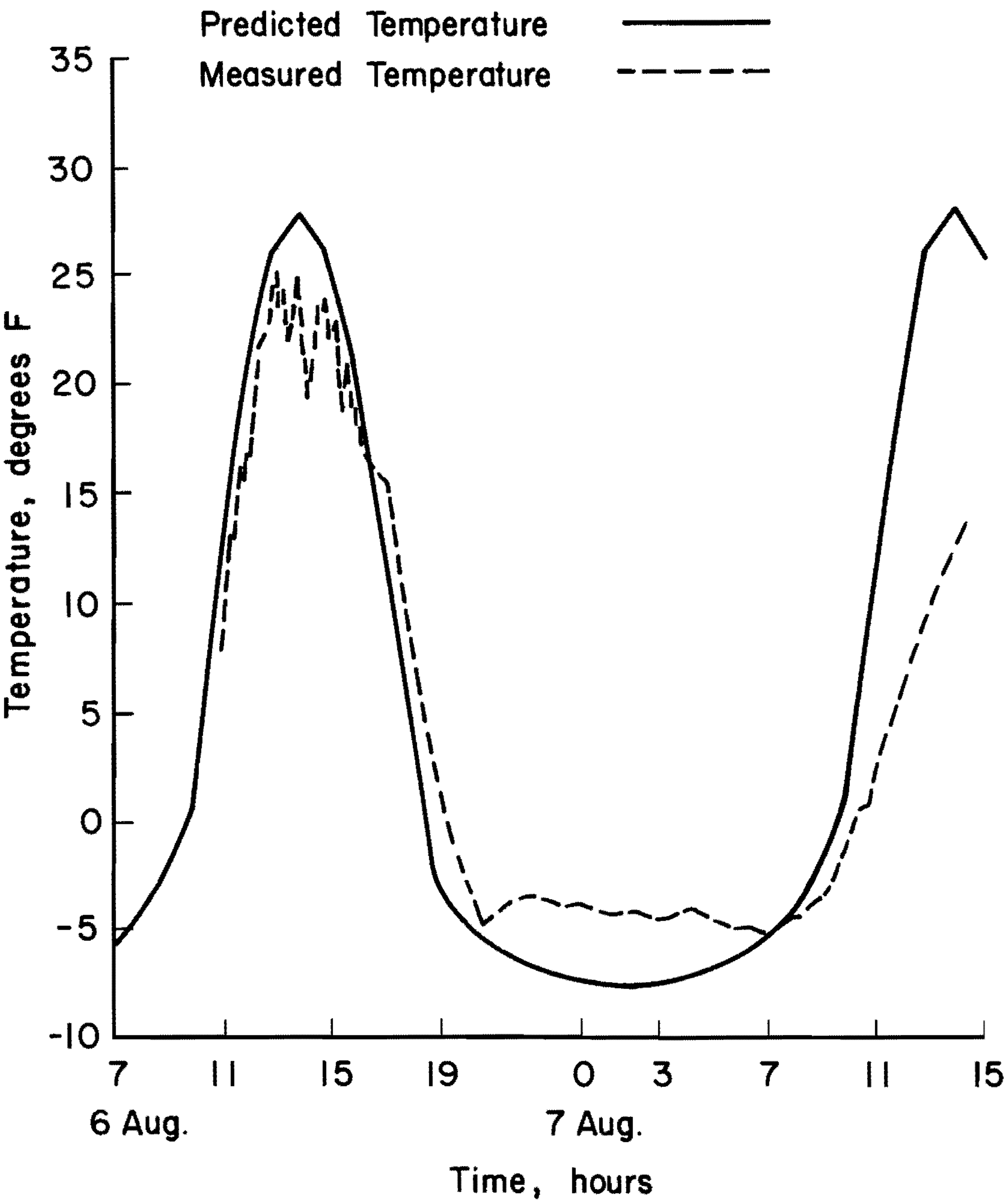


Fig 4. 2. Comparison of predicted and measured temperature differential (Ref 7).

concrete and a source for obtaining the pertinent daily weather information are also described. The estimated temperature parameters from computer program PTEMP compare reasonably well with the measured data.

CHAPTER 5. DETERMINATION OF THE REQUIRED NUMBER OF DYNAFLECT DEFLECTIONS

The assumption concerning the normally distributed population of deflections is a basic step toward the determination of sample size. Statistical procedures described in the first section were used on a sample of the Dynaflect data (collected in Project 256) to check and validate the assumption of normal distribution. In the later sections, a procedure is developed for determining the required number of Dynaflect deflections based on sound statistical theory. This procedure is an improvement and an extension of the study presented in Ref 5.

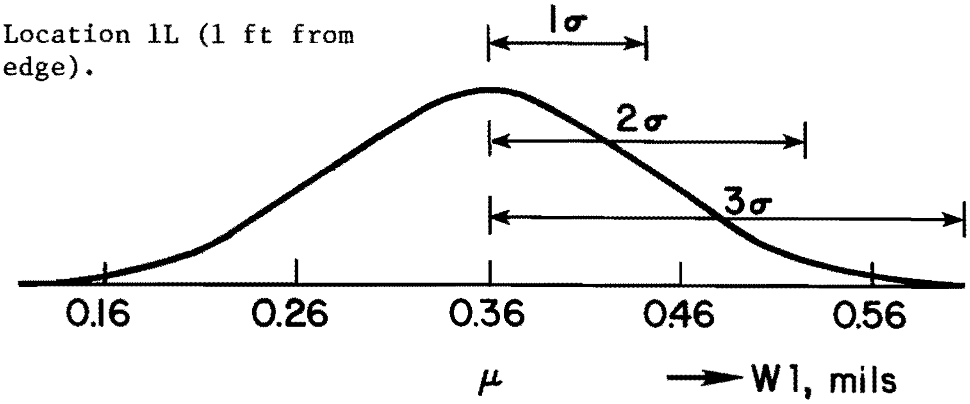
DISTRIBUTION OF DEFLECTIONS

Normality Tests

A number of procedures used for making statistical inferences from sampled deflections are based on the assumption that the population being sampled is (or is at least approximately) normally distributed. There are several procedures available to decide whether the normality assumption is reasonable.

Empirical Rule. The characteristics of normal distribution can be used to make an informal check on the normality assumption. Figure 5.1 illustrates examples of hypothetical continuous probability distribution which is normal. A normal distribution can be completely defined by the two parameters population mean, μ , and population standard deviation, σ. The estimate of μ is the sample average $\overline{W}$ which is a measure of location of the sample. Standard deviation is a measure of the spread of the distribution and can be estimated from the sample standard deviation, s. The probability that a single observation will fall within $\pm\sigma$, 2σ or $\pm 3\sigma$ is, respectively, around 0.68, 0.95, or 0.997. This has led to an empirical rule for checking normality (Ref 20).

(a) Location 1L (1 ft from edge).



(b) Location 4L (3 ft from edge)

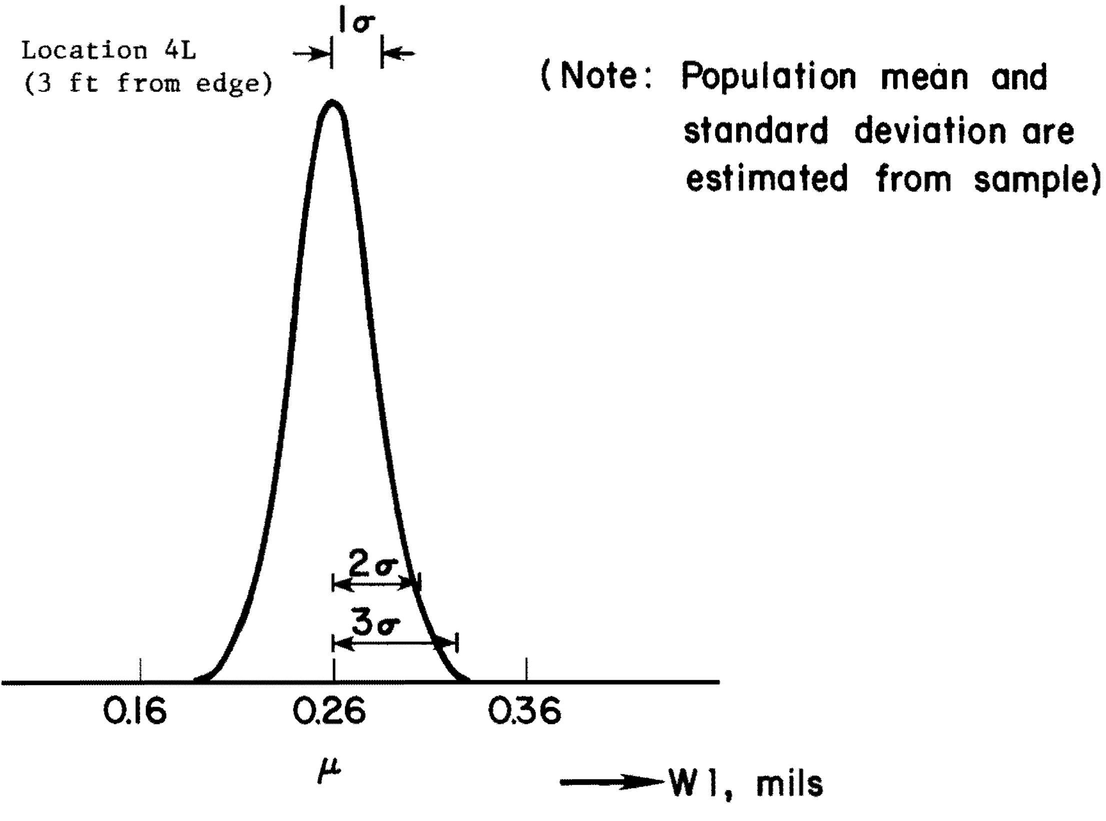


Fig 5.1. Examples of theoretical normal distributions at edge (1L) and wheelpath (4L) locations on rigid pavement.

If

1. $\left| \text{number in } \bar{W} - s, \bar{W} + s - 0.68n \right| \geq 1.41 \sqrt{n}$ (5.1)
2. $\left| \text{number in } \bar{W} - 2s, \bar{W} + 2s - 0.95n \right| \geq 0.654 \sqrt{n}$ (5.2)

or

3. $\left| \text{number in } \bar{W} - 3s, W + 3s - 0.997n \right| \geq 0.164 \sqrt{n}$ (5.3)

then the assumption of normality is of doubtful validity (where n = number of observations in the sample).

Use of Probability Paper. An informal check on the normality assumption can also be made by plotting the sample data points on the special normal probability paper. A sample drawn from a normally distributed population should give roughly a straight line plot on this specially constructed paper.

Goodness-of-Fit Tests. These statistical tests are used to compare the observed sample distribution with the theoretical distribution of the population. There are several goodness-of-fit tests used by statisticians. The commonly used tests are the chi-square test, the Kolmogorov-Smirnov test, and the Shapiro-Wilk test (Ref 20).

Application of Normality Tests to Sampled Deflection Data Dynaflect Deflection Sample

The variability in the deflection measurements can occur due to (1) random error, (2) equipment and operator errors, and (3) inherent variability due to subgrade soil and pavement characteristics. In our case the selection of pavement test sections are based on the same subgrade soil. The mistakes due to faulty equipment or human errors can not be considered in normality tests. The variability due to only chance errors is considered in the population distribution. Another important aspect is location of the deflection measurements. As illustrated in Figs 2.2 and 2.5, the mean deflection is significantly different with respect to the distance of Dynaflect from the pavement edge. It may imply that the deflections are normally distributed but have different means and variances at each location.

The Dynaflect maximum deflection data collected at Columbus, Texas (Ref 7) during 1981 have been used in this study. Random samples were drawn from this data set and their plots on normality paper were checked. They significantly deviated from a straight line, and the data were therefore divided into subsets with respect to the distance from the pavement edge.

Tests for Normality Assumption. Tests for normality made on random samples drawn from the subsets showed that the deflection data are normally distributed. However samples corresponding to different distances from the pavement edge correspond to populations with theoretical normal distribution having different means. The normality tests performed on a random sample of 28 sensor 1 deflections measured at 3 feet from the pavement edge, i.e., in the wheelpath are described in the following paragraphs.

Table 5.1 shows the results of applying the empirical rule. It can be seen that none of the inequalities are satisfied; therefore an assumption of normality is presumably correct. The plot of the sampled data points on a normality paper is approximately a straight line (Fig 5.2). A detrended normal plot was also generated. This plot indicates that the sample is probably drawn from a normally distributed population if the data points are clustered about zero on the vertical axis, as illustrated in Fig 5.3.

The Kolmogorov-Smirnov (2-tailed) test was employed as a goodness-of-fit test to check the normality assumption. It is a nonparametric test in which the null hypothesis states that the population is a normal distribution. The mean and standard deviation of the population are estimated from the sample. The results are presented in Table 5.2. Additionally, based on 2-tailed probability associated with the Kolmogorov-Smirnov Z statistic the null hypothesis cannot be rejected. Therefore it is reasonable to assume that the

TABLE 5.1. NORMALITY CHECK BY EMPIRICAL RULE

Sample Size (n)	Mean, mils $(\bar{x})$	Standard Deviation (s)
28	0.263	0.013

Intervals	Observations in the Intervals
1 : $(\bar{x} - s, \bar{x} + s) = 0.250, 0.276$	17
2 : $(\bar{x} - 2s, \bar{x} + 2s) = 0.237, 0.289$	27
3 : $(\bar{x} - 3s, \bar{x} + 3s) = 0.224, 0.302$	28

Inequalities

1 : $|17 - 0.68 \times 28| \geq 1.41 \sqrt{28}$

2 : $|27 - 0.95 \times 28| \geq 0.654 \sqrt{28}$

3 : $|28 - 0.997 \times 28| \geq 0.164 \sqrt{28}$

Result: Since none of the three inequalities are satisfied, an assumption of normality is plausible.

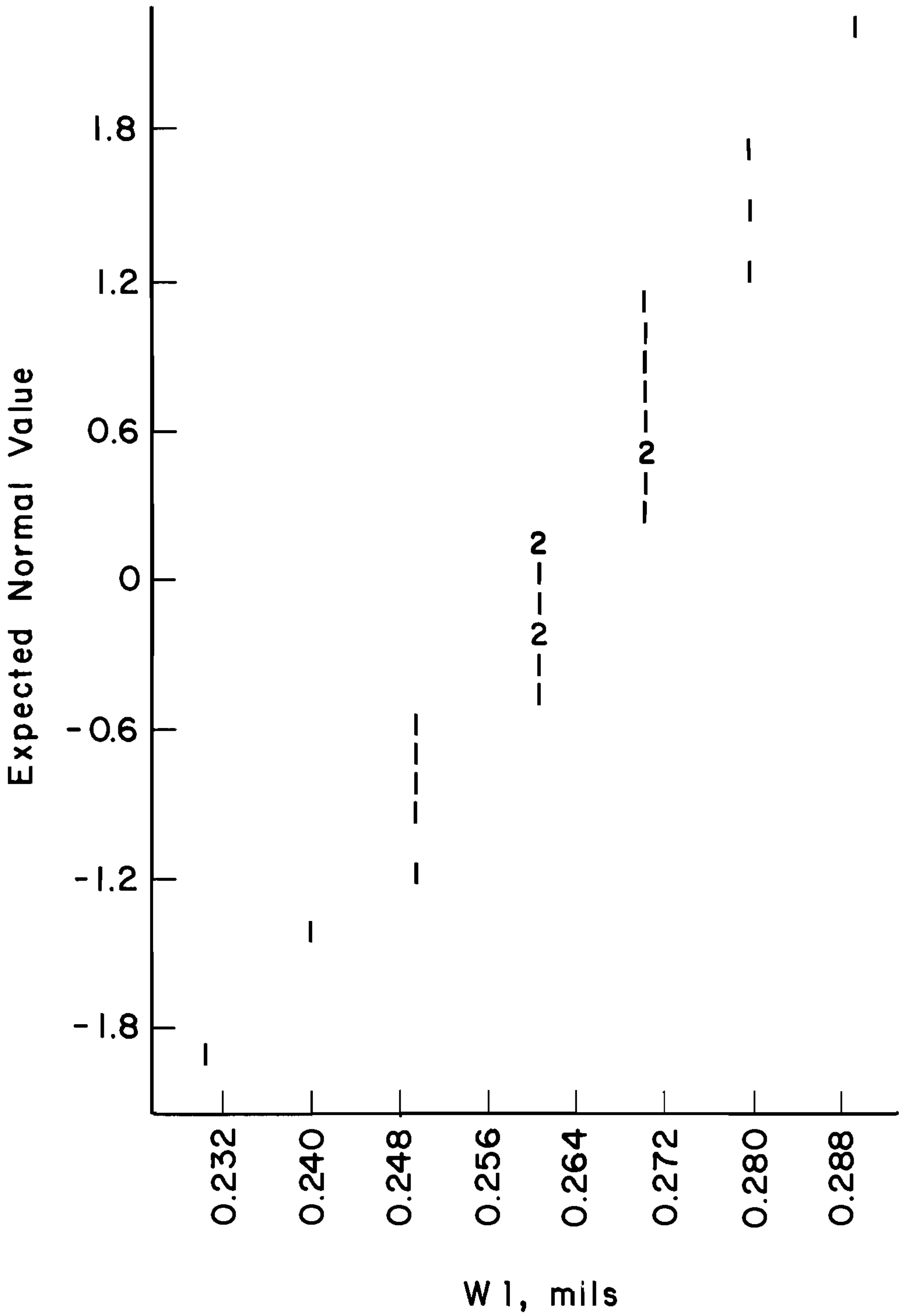


Fig 5.2. Plot of W1 deflection sample data on normal probability paper.

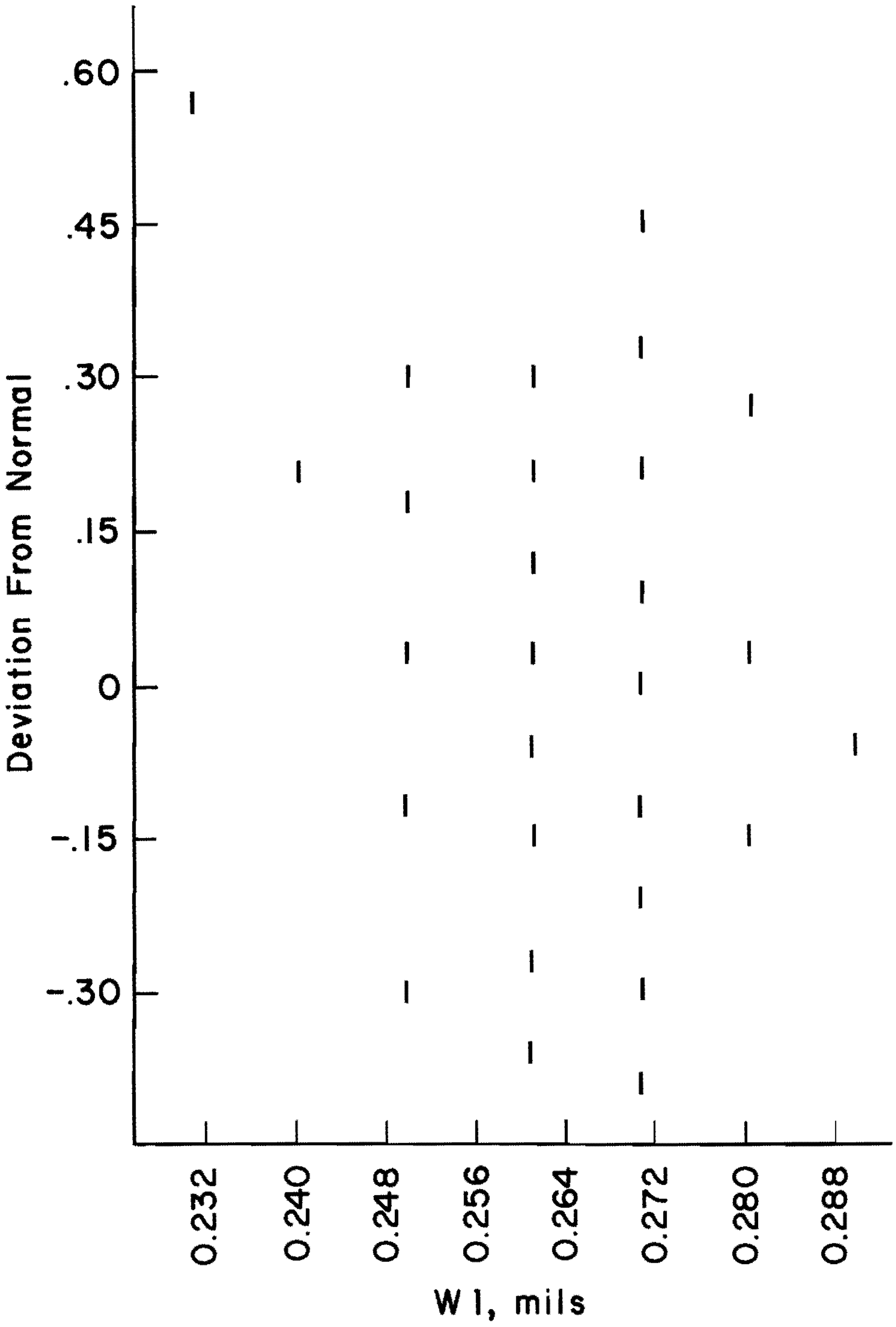


Fig 5.3. Detrended normal plot of sample W1 deflection data.

TABLE 5.2. KOLMOGOROV - SMIRNOV GOODNESS OF FIT TEST ON SAMPLE DEFLECTIONS

1. Null Hypothesis, H_o : The observed distribution comes from a normally distributed population.

2. Alternate Hypothesis, H_a: The observed distribution comes from a population that does not have a normal distribution.

3. Test Statistics: D_α = Maximum absolute differences between observed and theoretical frequencies expressed as proportions.

   At $\alpha = 0.05$; $D_\alpha = 0.25$ for $n = 28$ (Ref 23).

4. Criterion: Reject H_o if $D > 0.25$;

5. Assuming normal distribution with mean = 0.2620 and standard deviation = 0.013 estimated from the samples; it is found that:

   $D = 0.1728$.

6. Since $D(0.1728) < D_\alpha(0.25)$; Do not reject H_o. In other words, the assumption of normal distribution is reasonable.

distribution of the population is normal. Figure 5.4 illustrates the frequency distribution of the sampled data.

The results and discussions presented so far indicate that (1) the normality assumption for these Dynaflect deflections appears reasonable and (2) the deflection data collected at different distances from the pavement edge should be treated separately keeping in view that these may be from normally distributed populations with different means and/or variances.

Development of a Procedure to Determine the Required Number of Dynaflect Deflections for Materials Characterization Purposes in Rigid Pavements. Several attempts have been made in the past to estimate the sample size of pavement deflections under the assumption that deflection measurements are normally distributed. This assumption has been validated in the preceding section of this chapter.

Generally, if the value of σ (universe standard deviation) is known, a level of confidence is specified, and the allowable error (e) in estimating μ (universe mean) is given , a confidence interval of μ can be produced by selecting a sample of the correct size (Ref 22). Reference 5 presents previous work related to the estimation of deflection sample size for materials characterization of in-service rigid pavements.

The formal expression to determine required sample size is written as

$$n_r = \left[\frac{Z_\alpha \sigma}{e} \right]^2 \tag{5.4}$$

where

n_r = required sample size

Z_α = the abscissa of the normal curve that cuts off an area (level of significance) at the tails, and

e = allowable error.

$\hat{\sigma}$ is the unbiased estimate of the universe standard deviation, σ , and is obtained from a representative sample by

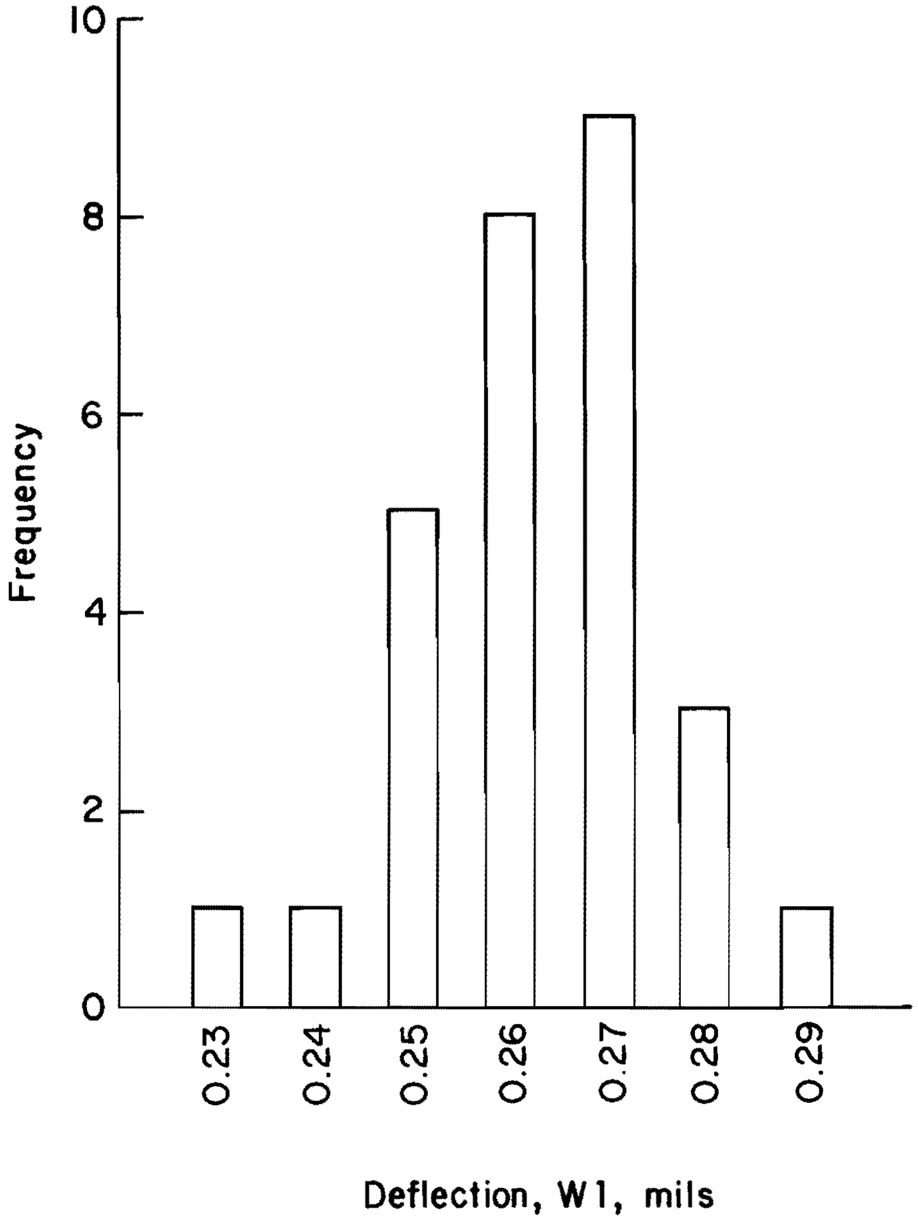


Fig 5.4. Frequency distribution of the Dynaflect Sample data.

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \overline{X})^2}{n-1}} \qquad (5.5)$$

where

X_i = value of the sample's i^th^ observation,
n = sample size, and
$\overline{X}$ = sample mean.

Since $\hat{\sigma}$ is the parameter commonly available, a Student's t distribution should be used according to statistical theory. Thus, Eq 5.4 can be modified as follows:

$$n_r = \left[\frac{t_\alpha \hat{\sigma}}{e} \right]^2 \qquad (5.6)$$

where

t_α = t-value corresponding to a certain combination of level of significance, α , and number of degrees of freedom.

Number of degrees of freedom (d. f.) is defined as the sample size minus one (n_r - 1).

Equation 5.6 computes the required number of deflections for a particular pavement section if $\hat{\sigma}$ is used instead of the universe standard deviation. Equation formula 5.6 is very seldom used because t_α is a function of the sample size, which is what must be determined, and an iterative process needs to be followed until the value of t_α input is equal to that corresponding to the final sample size minus one (n_r - 1).

However, any of both equations provides an estimate of the required sample size for a given section, disregarding its length. Hence, in general, for sections with similar standard deviations, allowable errors, and Z_α (or

t_α) values, basically the same required number of deflections is obtained for both a short section and a considerably longer section.

This serious incongruity can be surmounted by considering the fact that for materials characterization purposes in rigid pavements the universe or population of deflections is a finite number for a given design section, which makes necessary the application of a finite multiplier, namely

$$\frac{N - n_r}{N - 1}$$

where

N = population size.

Deflections for materials characterization are generally taken at a midslab position to minimize the effect of discontinuities and temperature on recorded deflections. For practical purpose, only one deflection measurement is required between successive discontinuities in the longitudinal direction along a certain lane and within a selected pavement design section, since an interior loading position should be approximated in the field in order to use elastic layered theory to back-calculate the pavement layer stiffnesses.

$$N = \frac{L}{\overline{S}} \qquad (5.8)$$

where

L = pavement section length, feet, and

$\overline{S}$ = average spacing between successive discontinuities in the longitudinal direction, feet.

$\overline{S}$ can be determined from condition survey information. In the case of continuously reinforced concrete pavements the average crack spacing should be used, whereas for jointed pavements the average joint spacing should be estimated.

It must be pointed out that it is assumed that sample size is to be computed after pavement design sections are established. The common procedure followed for selecting design sections is to plot previous deflection measurements to scale as a function of distance; the roadway can then be divided into sections based on stratified variation of deflection data. Sections are selected subjectively, according to the plotted profile of the deflection parameters. The reader should consult Refs 4 and 5 for a more detailed explanation about the selection of design sections.

If σ is unknown, the estimated standard error of the mean of a finite universe is computed:

$$\hat{\sigma}_{\bar{x}} = \frac{\hat{\sigma}}{\sqrt{n_r}} \sqrt{\frac{N - n_r}{N-1}} \tag{5.9}$$

where

$\hat{\sigma}_{\bar{x}}$ = estimated standard error of the mean.

Now, a new expression to determine the required number of Dynaflect deflections can be derived.

Let the allowable error, e, be equal to

$$e = \bar{x} - \mu \tag{5.10}$$

e can also be expressed as

$$e = t_\alpha \frac{\hat{\sigma}}{\sqrt{n_r}} \sqrt{\frac{N - n_r}{N-1}} \tag{5.11}$$

$$e = t_\alpha \hat{\sigma} \sqrt{\frac{N}{n_r (N-1)} - \frac{1}{N - 1}}$$

Solving for n_r, after some algebraic simplifications

$$n_r = \frac{N\, t_\alpha^{2}\, \hat{\sigma}^{2}}{(N - 1)\, e^{2} + t_\alpha^{2}\, \hat{\sigma}^{2}} \tag{5.12}$$

By dividing both the numerator and the denominator of the right-hand side of Eq 5.12 by $t_\alpha^{2}\ \hat{\sigma}^{2}$, the following alternate equation is obtained

$$n_r = \frac{N}{\dfrac{(N - 1)\, e^{2}}{t_\alpha^{2}\, \hat{\sigma}^{2}} + 1} \tag{5.13}$$

Torres-Verdin and McCullough (Ref 5) correlated slab thickness variation with sensor 1 mean deflection, and since allowable error is often expressed as a percent of sensor 1 mean deflection, it was found that an allowable error of 5 percent of the sensor 1 mean deflection resulted in a ± 0.5 in variation thickness, which, in turn, can be expressed as a percent of the sensor 1 mean deflection.

Computations were made to find the required number of Dynaflect deflection measurements for various combinations of values of $\hat{\sigma}$, e and N, and for two different confidence levels (90 and 95 percent).

The confidence interval was defined as

$$\mu \le \bar{x} + t_\alpha \hat{\sigma}_{\bar{x}} \tag{5.14}$$

Hence, one-tail hypothesis tests were used to determine sample size, for which the major concern was to state at a given confidence level that was less than or equal to the upper limit of the interval corresponding to that confidence level.

Likewise, the required deflection sample size can also be computed using a normal distribution approach. Assuming that σ is equal to $\hat{\sigma}$, Eq 5.13 can be modified as follows:

$$n_r = \frac{N}{\frac{(N-1)\,e^2}{Z_\alpha^{\,2}\ \hat{\sigma}^{\,2}} + 1} \qquad (5.15)$$

The above equation has an advantage over the Student's-t-distribution approach that Z_α is solely dependent on the particular confidence level selected, while t_α is obtained for a given confidence level and number of degrees of freedom.

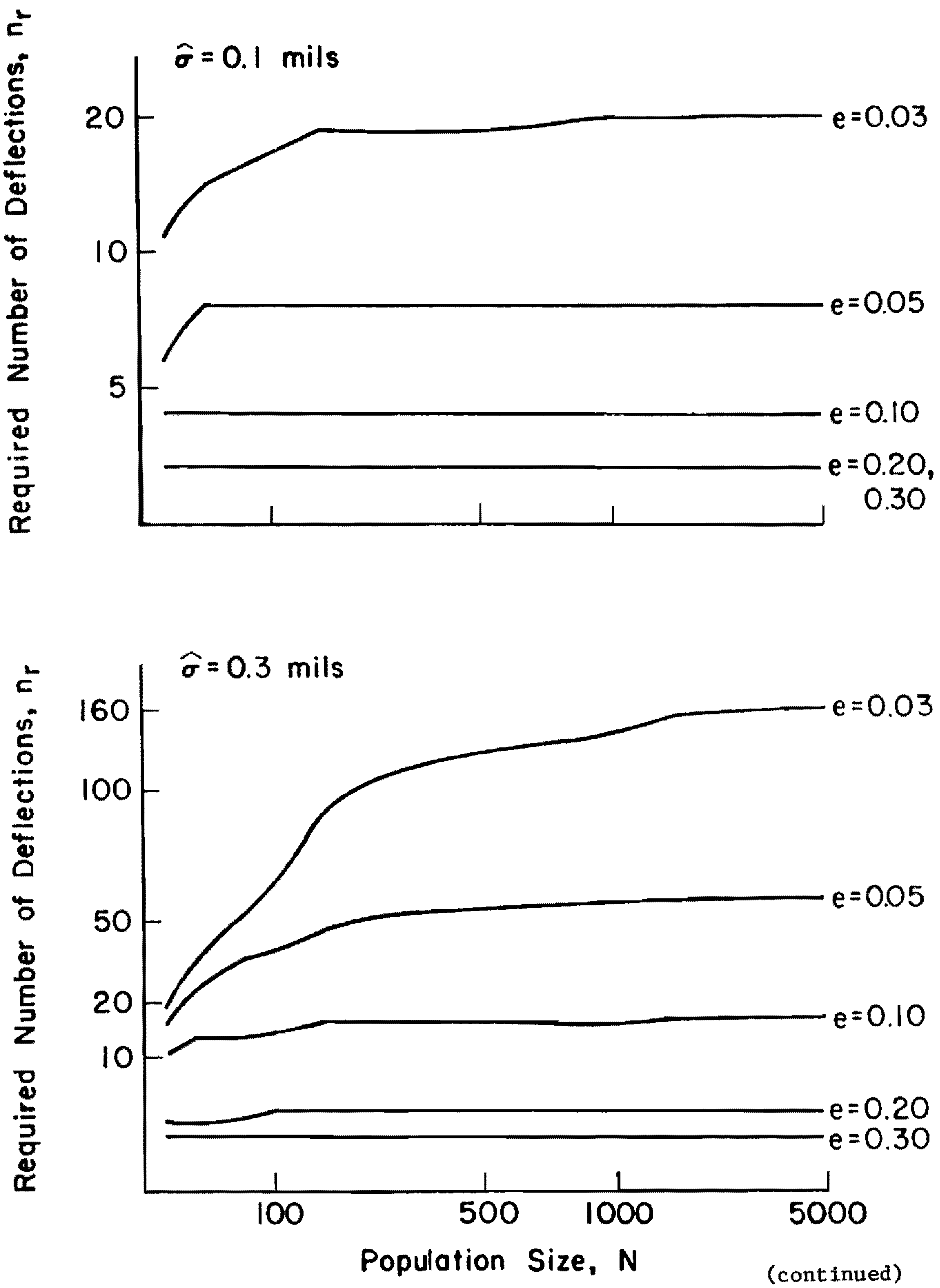
In order to determine n_r when employing the Student's-t-distribution approach, an iterative procedure was followed because number of degrees of freedom is equal to sample size minus one (n_r - 1) and n_r is unknown at the outset of the analysis. First, a value of t_α was assumed in Eq 5.13 to obtain an initial n_r; the t_α corresponding to the initial n_r was input into the same equation to compute a second n_r, and this process was repeated until the number of degrees of freedom plus one (d.f. + 1) was approximately equal to the resulting n_r. It is important to mention that n_r was rounded up to the next integer because sample size for Dynaflect deflection measurements is always an integer number.

The following general conclusions can be drawn from the above study:

(1) The normal-distribution approach results in sample sizes similar to ones obtained from the application of formula 5.13. Besides, Z_α does not vary with sample size and t_α does.

(2) The required number of Dynaflect deflections increases with increasing $\hat{\sigma}$, population size and confidence level. An increase in n_r is also observed when the allowable error, e, is decreased.

Figures 5.5 and 5.6 graphically show the results obtained for different combinations of $\hat{\sigma}$, e, and N. Both the x and y axes were deformed so that the wide range of values corresponding to N and n_r, respectively, could be accommodated. These charts are recommended when it is not possible to use Eq 5.16, which is a simplification of Eq 5.15.



(continued)

Fig 5.5. Required deflection sample size for various combinations of $\hat{\sigma}$, e, and N and a 90 percent confidence level (e is given in mils).

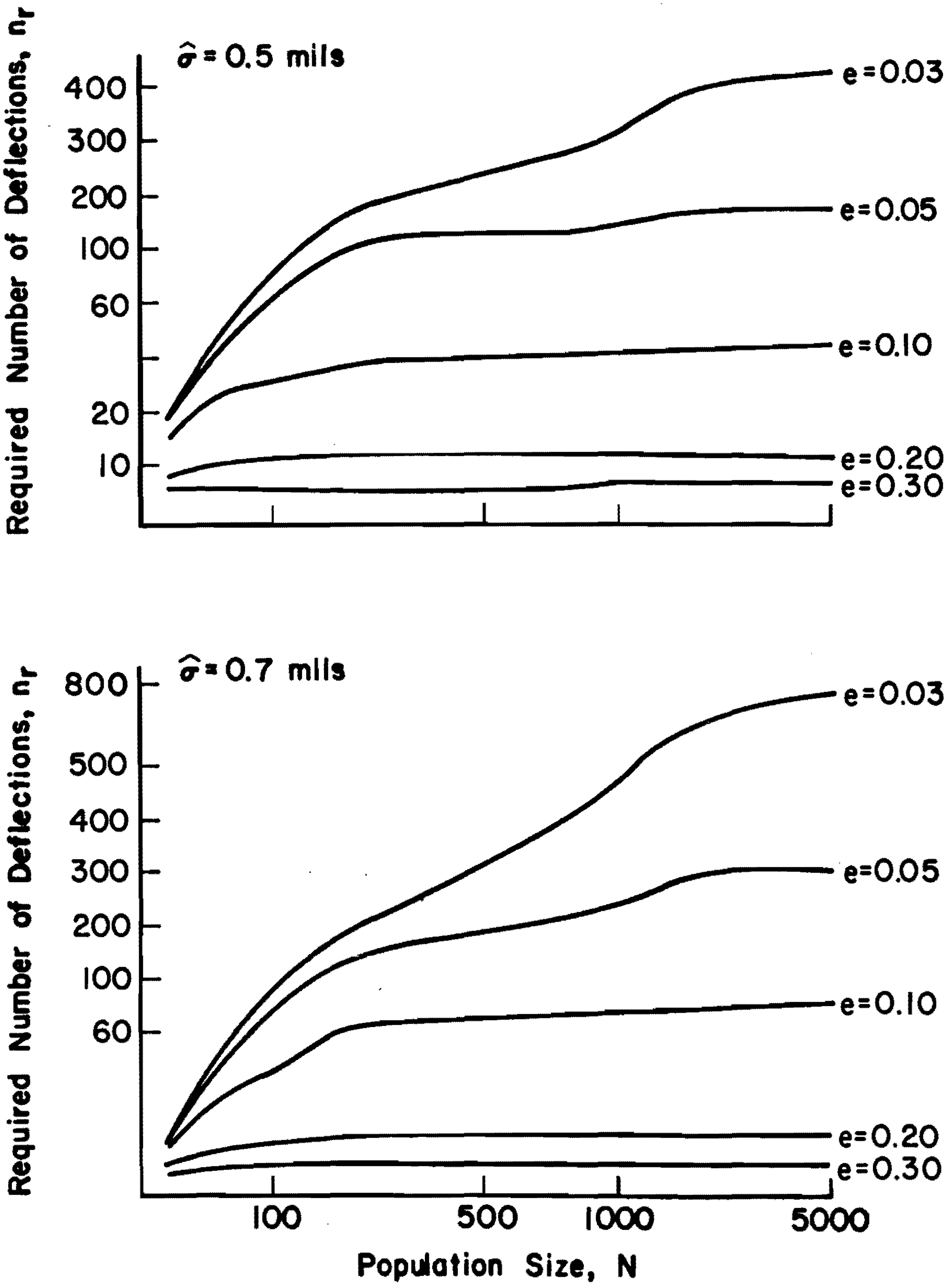


Fig 5.5. (continued).

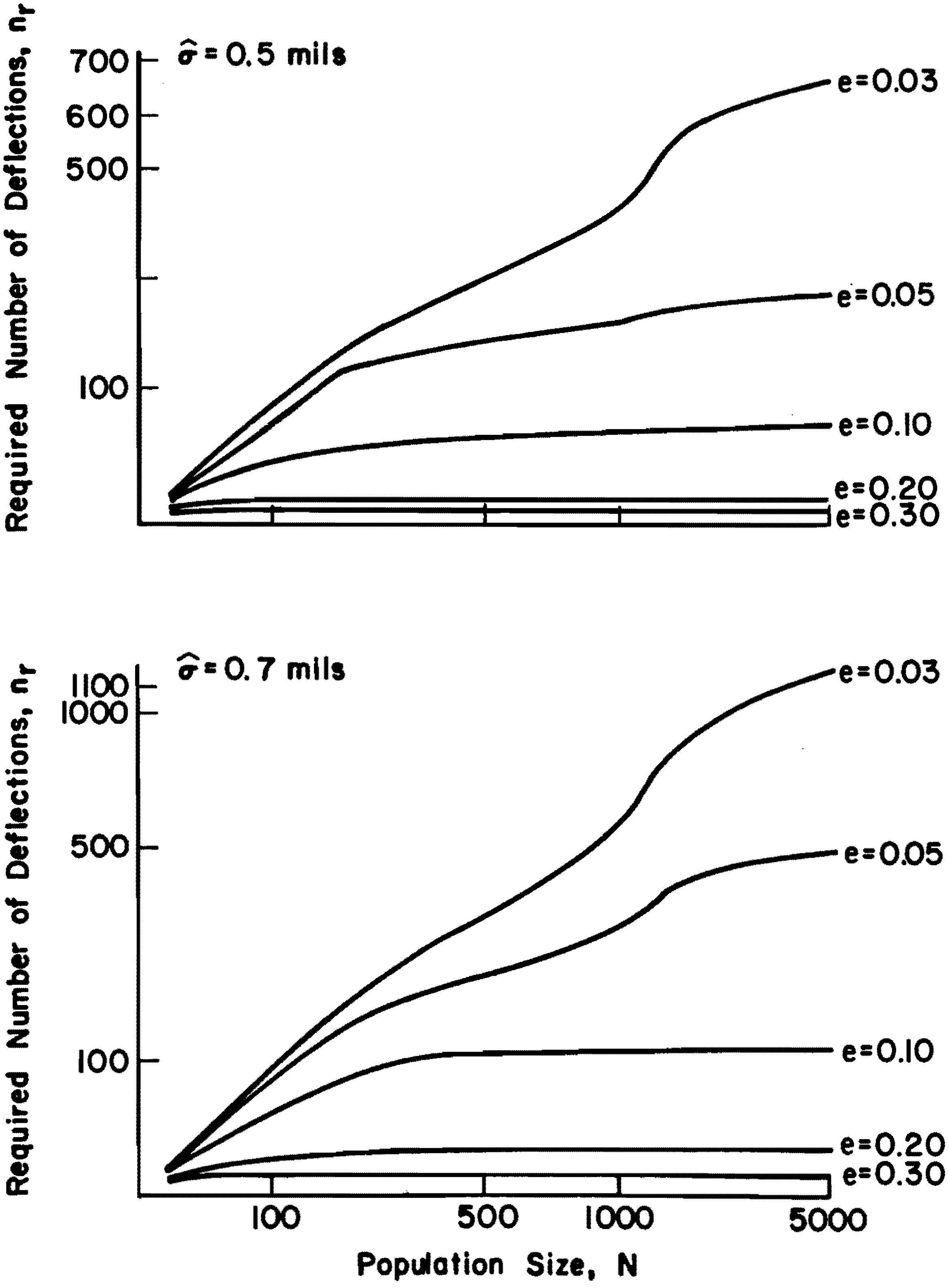
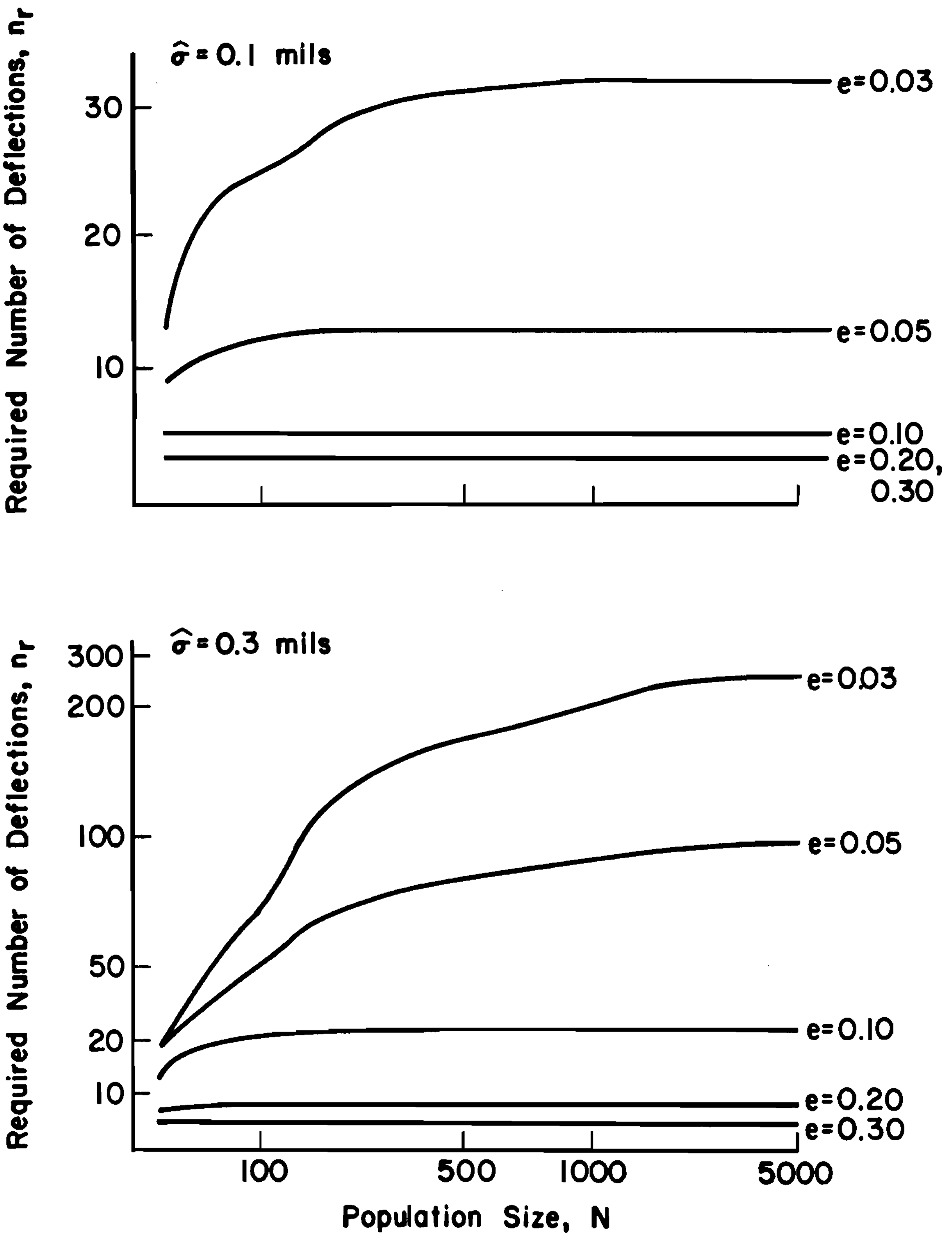


Fig 5.6. (continued).



(continued)

Fig 5.6. Required number of Dynaflect deflections for various combinations of $\hat{\sigma}$, e, and N and a 95 percent confidence level (e is given in mils).

Generally, the size of the population is sufficiently large so that the difference between N and N-1 is negligible. Hence, the finite multiplier can be modified.

$$\frac{N - n_r}{N - 1} \cong \frac{N - n_r}{N}$$

Finally, a less complicated version of Eq 5.12 is obtained:

$$n_r = \frac{1}{\frac{e^2}{Z_\alpha^2 \hat{\sigma}^2} + \frac{1}{N}} \qquad (5.16)$$

Values for Z_α depending on the selected confidence level are provided in Table 5.3. In some instances a required sample size of less than two measureents can be obtained; however, a minimum value of two should always be used.

If no previous deflection information is available about a particular pavement section, the required number of Dynaflect deflections could be estimated as the testing is conducted by computing $\hat{\sigma}$ and $\bar{x}$ corresponding to the sensor 1 deflections taken so far. This could be done for every additional deflection until both σ and $\bar{x}$ remained reasonably constant. The process described above could be made very simple by connecting a microcomputer to the device in which the deflections are permanently recorded. Likewise, if this improvement were made, either Eq 5.15 or 5.16 could be easily included in a computer program to calculate the required number of Dynaflect deflection measurements.

Determination of the Required Sample Size of Dynaflect Deflections for Void Detection and Load Transfer Evaluation

For void detection and load transfer evaluation, the sample size would depend on the condition of the pavement. Data from condition surveys are very useful in trying to locate the areas susceptible to voids in a given pavement section in which there is evidence of pumping along the pavement

TABLE 5.3. VALUES OF Z_α FOR VARIOUS CONFIDENCE LEVELS

Confidence Level, α, Percent	Z_α
80.0	0.842
85.0	1.036
90.0	1.282
95.0	1.645
97.5	1.960
99.0	2.326

edge. Then, the Dynaflect could be taken to the site so that deflections could be analyzed to either confirm or deny the findings from the condition survey.

The required number of Dynaflect deflections for load-transfer evaluation is a decision that is left to engineering judgement, since a visual inspection of the joints and/or cracks is required prior to using the Dynaflect. Wide crack widths may indicate low load transfer in CRC pavements since in these pavements coarse aggregate interlock is an important influence on load transfer across a crack.

SUMMARY

The commonly employed normality assumption for deflection data was checked in the first part of this chapter. The normality checks were performed on a random sample of the Dynaflect deflection data. It has been The normality assumption is reasonably acceptable for the set of data tested.

A detailed procedure was also developed to determine the number of Dynaflect deflection basins on rigid pavement required for material characterization. Similarly recommendations are also made regarding sample size for the purpose of void detection and load transfer evaluation.

CHAPTER 6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

The effects on measured deflections of seasons of the year, temperature, and distance from the pavement edge and other pavement characteristics such as voids and discontinuities on deflections are described in this report. The influence of placement and replicate errors and effects of rigid layer and variations in slab thickness are also discussed.

Guidelines for the applications of Dynaflect deflections to material characterization, void detection and load transfer evaluation are presented. A procedure for estimation of pavement temperature from daily weather reports is described to provide an alternative to the actual measurement. The assumption of normality has been checked on a random sample of the Dynaflect deflections based on sound statistical theory.

CONCLUSIONS

Factors Affecting Deflections and Sources of Errors

The major findings regarding effects of different factors and sources of errors on deflections measured on rigid pavements are stated below.

(1) Temperature differential is the most important temperature variable influencing deflections on rigid pavement. The extent and nature of this influence depends on distance from pavement edge and the load.

  (a) Edge deflections are significantly affected by temperature differential and require a temperature correction.
  (b) The influence of temperature differential on deflections measured in the wheelpath or near the center line is not of practical significance.

(2) Seasonal changes in the deflections on CRC pavements are not significant. However deflections on other types of rigid pavements show seasonal effects. The findings for CRC pavements are interesting but based on limited data and somewhat in conflict with the present data and belief. Further research is needed in this area.

(3) It is important to recognize that distance of the Dynaflect with respect to pavement edge should be based on the purpose for which the deflection data is required. Pavement characteristics such as void size and transverse cracks or joints should also accordingly be considered in the selection of test location.

(4) The loading wheels of the Dynaflect should be placed as close as possible to the designated test position on the pavement. Any data where placement error is greater than ± 5 inches tolerance should be dropped. Dynaflect deflection data is very reliable and coefficient of variation is generally less than 10 percent.

(5) Infinite subgrade is generally assumed in the calculation of subgrade modulus from a measured deflection basin. This modulus value should be reduced to account the effect of any rigid layer existing below a finite thickness of the subgrade.

Applications of the Dynaflect Deflections

Material Characterization. The principal conclusion related to the procedure of material characterization from Dynaflect deflections are summarized as follows:

(1) Guidelines presented in Chapter 3 can be used to estimate the initial values of Young's moduli of pavement layers and subgrade.

(2) Step by step procedures presented in the text can be used to backcalculate Young's moduli by fitting the measured deflection basin, either using computer based iterative methods or a graphical method.

(3) Correction of subgrade modulus for the presence of a rigid layer results in a reduction in the final subgrade modulus. However, a rigid bottom can be simulated in any layered theory computer program by assigning a very large value (say 10^{99} psi) of Young's modulus to the last layer.

(4) The Dynaflect deflection basin should be measured in midspan position and in the wheelpath or near the center line of the outside line for the purpose of material characterization.

Void Detection

(1) Dynaflect deflections are to be measured at 1 ft from pavement edge and compared with midspan deflections measured at the center of the lane.

(2) The Dynaflect edge deflections measured for void detection and for checking the effectiveness of grouting are to be corrected to remove the influence of temperature differential.

Load Transfer. The conclusions from the study of load transfer evaluation are as follows:

(1) Load transfer at transverse cracks can be estimated by comparing the Dynaflect sensor 1 deflections at the crack to the deflections at midspan between cracks.

(2) The diagnostic checking of the structural condition of pavements at transverse cracks can be made by the deflection ratio (d_c/d_i) obtained from Dynaflect deflection measurements.

Reflection Cracking Analysis

Those joints (or cracks) whose deflection factors exceed the maximum deflection factor should be subjected to an appropriate rehabilitation measure before overlay placement.

Estimation of Temperature in Concrete Slab

(1) If it is not possible to actually measure temperatures in concrete slab then temperature differential can be estimated from

   (a) daily maximum and minimum air temperature,
   (b) solar radiation data,
   (c) wind speed, and
   (d) thickness of slab.

(2) Computer program PTEMP can be used to estimate temperature at any depth in a concrete slab.

(3) The model predictions for temperatures compare very well with the measured temperature data.

Determination of Required Number of Dynaflect Deflections

Check for Normality Assumption. A procedure for determining the normality of the distribution of the data have been presented.

Sample Size Determination. A simplified procedure has been developed and is presented that can be used to select the required deflection sample size based on the section length for the purpose of material characterization.

RECOMMENDATIONS

The Dynaflect deflection measurements on rigid pavements are made for structural evaluation. The following recommendations are based on the findings of this report.

(1) This report provides detailed background material to:

   (a) determine sample size and performing deflection measurements to obtain reliable and useful data and

   (b) analyze the respective deflection data according to the purpose for which the Dynaflect was used.

(2) Specific guidelines in Chapter 3 of this report should be used for analyzing the deflection data to do material characterization, void detection and load transfer evaluation.

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