NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **327**

DETERMINING ASPHALTIC CONCRETE PAVEMENT STRUCTURAL PROPERTIES BY NONDESTRUCTIVE TESTING

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

TRANSPORTATION RESEARCH BOARD EXECUTIVE COMMITTEE 1990

OFFICERS

Chairman: *Wayne Muri, Chief Engineer, Missouri Highway & Transportation Department*
Vice Chairman: *C. Michael Walton, Bess Harris Jones Centennial Professor and Chairman, College of Engineering, The University of Texas at Austin*
Executive Director: *Thomas B. Deen, Transportation Research Board*

MEMBERS

JAMES B. BUSEY IV, *Federal Aviation Administrator, U.S. Department of Transportation* (ex officio)
GILBERT E. CARMICHAEL, *Federal Railroad Administrator, U.S. Department of Transportation,* (ex officio)
BRIAN W. CLYMER, *Urban Mass Transportation Administrator, U.S. Department of Transportation* (ex officio)
JERRY R. CURRY, *National Highway Traffic Safety Administrator, U.S. Department of Transportation* (ex officio)
FRANCIS B. FRANCOIS, *Executive Director, American Association of State Highway and Transportation Officials* (ex officio)
JOHN GRAY, *President, National Asphalt Pavement Association* (ex officio)
THOMAS H. HANNA, *President and Chief Executive Officer, Motor Vehicle Manufacturers Association of the United States, Inc.* (ex officio)
HENRY J. HATCH, *Chief of Engineers and Commander, U.S. Army Corps of Engineers* (ex officio)
THOMAS D. LARSON, *Federal Highway Administrator, U.S. Department of Transportation* (ex officio)
GEORGE H. WAY, JR., *Vice President for Research and Test Departments, Association of American Railroads* (ex officio)
ROBERT J. AARONSON, *President, Air Transport Association of America*
JAMES M. BEGGS, *Chairman, Spacehab, Inc.*
ROBERT N. BOTHMAN, *Director, Oregon Department of Transportation*
J. RON BRINSON, *President and Chief Executive Officer, Board of Commissioners of The Port of New Orleans*
L. GARY BYRD, *Consulting Engineer, Alexandria, Virginia*
L. STANLEY CRANE, *Retired, Former Chairman & Chief Executive Officer, Consolidated Rail Corporation*
RANDY DOI, *Director, IVHS Systems, Motorola Incorporated*
EARL DOVE, *President, Earl Dove Company*
LOUIS J. GAMBACCINI, *General Manager, Southeastern Pennsylvania Transportation Authority* (Past Chairman 1989)
KERMIT H. JUSTICE, *Secretary of Transportation, State of Delaware*
DENMAN K. McNEAR, *Vice Chairman, Rio Grande Industries*
WILLIAM W. MILLAR, *Executive Director, Port Authority of Allegheny County*
CHARLES L. MILLER, *Director, Arizona Department of Transportation*
ROBERT E. PAASWELL, *Professor of Transportation Engineering, Urban Transportation Center, University of Illinois at Chicago*
RAY D. PETHTEL, *Commissioner, Virginia Department of Transportation*
JAMES P. PITZ, *Director, Michigan Department of Transportation*
HERBERT H. RICHARDSON, *Deputy Chancellor and Dean of Engineering, Texas A&M University System* (Past Chairman 1988)
JOE G. RIDEOUTTE, *Executive Director, South Carolina Department of Highways and Public Transportation*
CARMEN E. TURNER, *General Manager, Washington Metropolitan Area Transit Authority*
FRANKLIN E. WHITE, *Commissioner, New York State Department of Transportation*
JULIAN WOLPERT, *Henry G. Bryant Professor of Geography, Public Affairs and Urban Planning, Woodrow Wilson School of Public and International Affairs, Princeton University*
PAUL ZIA, *Distinguished University Professor, Department of Civil Engineering, North Carolina State University*

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Transportation Research Board Executive Committee Subcommittee for NCHRP
WAYNE MURI, *Missouri Highway & Transportation Department* (Chairman)
LOUIS J. GAMBACCINI, *Southeastern Pennsylvania Transportation Authority*
FRANCIS B. FRANCOIS, *American Association of State Highway and Transportation Officials*
THOMAS D. LARSON, *U.S. Department of Transportation*
C. MICHAEL WALTON, *University of Texas at Austin*
L. GARY BYRD, *Consulting Engineer*
THOMAS B. DEEN, *Transportation Research Board*

Field of Materials and Construction
Area of Specifications, Procedures, and Practices
Project Panel D10-27

DENNIS E. DONNELLY, *Colorado Department of Highways* (Chairman)
HARVEY S. ALLEN, *Minnesota Department of Transportation*
GILBERT Y. BALADI, *Michigan State University*
JAMES P. DELTON, *Arizona Department of Transportation*
WILLIAM N. LOFROOS, *Florida Department of Transportation*
KEVIN STUART, *FHWA Liaison Representative*
GEORGE W. RING III, *TRB Liaison Representative*

Program Staff

ROBERT J. REILLY, *Director, Cooperative Research Programs*
LOUIS M. MACGREGOR, *Program Officer*
DANIEL W. DEARASAUGH, JR., *Senior Program Officer*
IAN M. FRIEDLAND, *Senior Program Officer*
CRAWFORD F. JENCKS, *Senior Program Officer*
KENNETH S. OPIELA, *Senior Program Officer*
DAN A. ROSEN, *Senior Program Officer*
HELEN MACK, *Editor*

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 327

DETERMINING ASPHALTIC CONCRETE PAVEMENT STRUCTURAL PROPERTIES BY NONDESTRUCTIVE TESTING

R. L. LYTTON, F. P. GERMANN, Y. J. CHOU and S. M. STOFFELS
Texas Transportation Institute
The Texas A&M University System
College Station, Texas

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST

Pavement Design and Performance
Bituminous Materials and Mixes
(Highway Transportation, Air Transportation)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D. C.
JUNE 1990

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP REPORT 327

Project 10-27 FY '84

ISSN 0077-5614

ISBN 0-309-04624-6

L. C. Catalog Card No. 90-70586

Price $11.00

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

Special Notice

The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers names appear herein solely because they are considered essential to the object of this report.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

FOREWORD

By Staff
Transportation Research Board

This report "Determining Asphaltic Concrete Pavement Structural Properties by Nondestructive Testing," along with the computer programs MODULUS and PASELS, will be of special interest to pavement engineers, those involved with pavement management systems, and engineers responsible for determining pavement conditions. The report contains the findings of research to improve the use of nondestructive testing devices, data, and analysis for determining pavement structural properties. The computer programs developed during this study assist in accurate and quick backcalculation of pavement layer moduli, as well as in determination of other pavement properties, such as load transfer at cracks and void areas between pavement layers.

An awareness of the increasing emphasis on management of pavements by highway and transportation agencies led to NCHRP Project 10-27 research in the use of nondestructive testing (NDT) data to determine pavement structural properties. Efficient and economical methods for determining the structural properties of existing pavements are necessary both at the network level, where data on the condition of many miles of pavements are needed, and at the project level, as input for design, rehabilitation, or maintenance. Use of NDT data with associated analysis methods, as presented in this report, provides the information on structural properties required by pavement engineers. The research was conducted by the Texas Transportation Institute, the Texas A&M University System, under the direction of Dr. Robert L. Lytton, Principal Investigator.

The findings indicate that more accurate data can be quickly obtained at both the network and project levels through the use of the falling weight deflectometer and the backcalculation computer program MODULUS. Outlined also are methods to reduce random and systematic errors, the latter through the computerized expert system, PASELS.

A MODULUS User's Manual is included in this report in Appendix F, and a User's Guide for the PASELS System is provided in Appendix H. The computer programs are available only from the McTrans Software Center at The Center for Microcomputers in Transportation, University of Florida, 512 Weil Hall, Gainesville, Florida 32611 (904/392-0378).

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 10-27 by the Texas Transportation Institute, Texas A&M University. The principal investigator for the Texas Transportation Institute was Robert L. Lytton, Research Engineer and Professor of Civil Engineering. The other authors of the report are Frederick P. Germann, Yein-Juin Chou, and Shelly M. Stoffels, Research Assistants, Texas Transportation Institute.

Many people have contributed to the preparation of this report. A number of them deserve to be listed as contributing authors: Thomas Scullion, Engineering Research Associate, Texas Transportation Institute; Roger E. Smith and Freddy L. Roberts, Associate Research Engineers and Associate Professors of Civil Engineering; Jacob Uzan, Senior Lecturer, Israel Institute of Technology; and Miguel Paredes, Engineering Research Associate, Texas Transportation Institute.

Technical guidance and assistance for the investigation was provided by Harold L. Von Quintus, President, and Peter Jordahl, Brent Rauhut Engineering and Marshall R.Thompson, Professor of Civil Engineering, University of Illinois.

Grateful acknowledgement is given to the Chairman and members of the Transportation Research Board Committee A2B05 on Strength and Deformation Characteristics of Pavement Sections for their cooperation in the bench mark study of backcalculation accuracy. The chairman was J. Brent Rauhut. Lynne H. Irwin, Professor of Civil Engineering at Cornell University, Per Ullidtz of the Technical Institute of Denmark, James Hall and Albert J. Bush III of the U.S. Army Engineer Waterways Experiment Station, and the manufacturers of the nondestructive testing equipment evaluated in this report rendered valuable assistance to this project.

DETERMINING ASPHALTIC CONCRETE PAVEMENT STRUCTURAL PROPERTIES BY NONDESTRUCTIVE TESTING

SUMMARY

Nondestructive testing of pavements offer an efficient, high production method of determining the properties of existing pavement layers. The National Cooperative Highway Research Program, in initiating Project 10-27, recognized its potential and also the need to develop methods of analyzing the data that are collected in a manner that is rapid, efficient, accurate and compatible with the high-volume data collection capabilities of modern nondestructive testing equipment. The objectives of this research are: (1) to provide methods and guidelines for calculating the structural properties of asphaltic concrete pavements, using nondestructive test data, for use in pavement analysis, design, rehabilitation, and other pavement management activities and (2) to develop detailed procedures to verify the method and to adjust the results for local conditions. A careful study of all types of nondestructive testing (NDT) equipment was made both for project level and network level data collected purposes. A utility decision analysis was used to select which of the commercially available equipment was most suitable for both purposes and, in each case, a falling weight deflectometer was found to be preferable.

A general analysis method was developed which may be used with any type of nondestructive deflection testing equipment, may use either layered linear elastic or finite element methods of backcalculating layer moduli, and is especially arranged to operate in a production mode to reduce the data from a deflection survey. This ability is provided by setting up a data base that usually consists of from 16 to 27 computed deflection basins calculated using moduli, which span the range of realistic values for each layer, and the known thickness of each layer. The method adopted in this report is the layered elastic method. The search for the best values of the layer moduli is conducted using interpolation between the calculated basins. This has been found to produce the final results some 30 to 100 times faster than other backcalculation methods that make use of iterative calculations. It is this speed that makes this procedure practical for use in a production mode of data reduction. The analysis method is incorporated into a microcomputer program named MODULUS, and a user's guide to the program is provided in an appendix.

Data collected in a mass inventory survey have uses at the network and project levels. At the network level, the major interest is in having data that can be used for comparing the relative stiffness and remaining life of each section of pavement in a network. At the project level, NDT data are used to determine not only the layer moduli at relatively frequent intervals but also the load transfer capability of cracks, the presence of voids between layers, the thermal effects of stabilized layers, the depth to bedrock and water tables, and other important site-specific data that are useful in planning and designing a rehabilitation effort and in providing realistic field data.

All of these uses, whether they are at the network or project level, require that the layer moduli be comparable to each other, that is, that they have either been measured at or corrected to the same conditions of load level, temperature, and loading duration or frequency.

A major part of this project has been devoted to developing and verifying methods

of making modulus corrections. This has required making numerous field measurements in different climatic zones throughout a complete year, measuring deflections, temperatures on the surface and beneath it, and soil moisture suction in the sublayers each month. These data provide a valuable source of information on the effects of load, temperature, and moisture on pavement layer moduli.

As important as the analysis and correction to standard conditions are, the identification and reduction of the errors in making accurate measurements of the moduli are of equal importance. There are two kinds of errors: random and systematic. Random errors are principally measurement errors from the load cells and motion sensors. They may be reduced by repeating the measurement. Systematic errors are more numerous and more difficult to reduce, and include erroneous assumptions made in the backcalculation process. If they are recognized, systematic errors can be corrected, but such correction requires experience. To compensate for the normal user's lack of such detailed experience and to assist in making the layer moduli as accurate as possible, an expert system has been developed for use with the backcalculation program. The expert system incorporates most of the rules-of-thumb and systematic procedures that were developed in this project for the correction of moduli and the reduction of the errors in the calculated moduli. The expert system provided with this report will assist the inexperienced in obtaining consistently acceptable layer moduli. It is incorporated in a microcomputer program named PASELS for which a user guide is provided in an appendix.

The backcalculated asphaltic concrete moduli were shown to be in good agreement with the laboratory-determined moduli provided that the error between the calculated and measured deflections does not exceed the accuracy of the deflection sensors, the layer thicknesses are known accurately, nearly isothermal conditions exist in each layer, and other factors prevail, as discussed in the report. If these are taken into account and expert analysis of the deflection data is applied, a coefficient of variation in a deflection survey of around 30 percent can be achieved consistently. The accuracy of backcalculating the modulus of asphaltic concrete for a specific basin, assuming that random errors are reduced by repetition of the load and systematic errors are reduced by use of an expert system, is judged to be in the order of 10 to 20 percent.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

RESEARCH PROBLEM STATEMENT

Nondestructive testing of pavements offers an efficient, high production method of determining the properties of existing pavement layers. The National Cooperative Highway Research Program, in initiating Project 10-27, recognized its potential and also the need to develop methods of analyzing the data that are collected in a manner that is rapid, efficient, accurate, and compatible with the high-volume data collection capabilities of modern nondestructive testing equipment.

The project statement for NCHRP Project 10-27 presents the need for this research as follows:

> An increasing responsibility of highway and transportation agencies is the maintenance, rehabilitation, and management of highways that have been built. Particularly with regard to asphaltic concrete pavements, this requires the use of efficient and economical methods for determining the structural properties of existing pavements. Use of nondestructive testing (NDT) data with associated analysis methods appears to have potential for determining these pavement structural properties. Several types of NDT equipment and analysis procedures are currently available for providing the desired information. Analysis procedures utilizing NDT data vary substantially in complexity, accuracy, and availability—making the selection of appropriate equipment and analysis methods for an individual agency's pavement management needs difficult.
>
> Up-to-date information on the application and limitations of available analysis procedures for determining asphaltic concrete pavement structural properties using NDT data is urgently needed.

OBJECTIVES AND SCOPE

The primary objectives of this research, as outlined in the project statement, reads as follows:

> (1) to provide methods and guidelines for calculating the structural properties of asphaltic concrete pavements, using nondestructive test data, for use in pavement analysis, design, rehabilitation, and other pavement management activities and (2) to develop detailed procedures to verify the methods and to adjust the results for local conditions.

The research was conducted in two phases. In the first phase, a careful study of all types of nondestructive testing (NDT) equipment was made both for project level and network level data collection purposes. A utility decision analysis was used to select which of the commercially available equipment was most suitable for both purposes and, in each case, a falling weight deflectometer was found to be preferable. The criteria used in evaluating the equipment and the relative weights assigned to each are given in Appendix K. Analysis methods were also studied to determine their applicability to the backcalculation of layer moduli; to the corrections that must be applied to bring these moduli to a standard condition of load, temperature, and loading frequency; and to correlations between NDT devices.

The second phase of the project developed a general analysis method, called program MODULUS, which may be used with any type of nondestructive deflection testing equipment. The program may use either layered linear elastic or finite element methods of backcalculating layer moduli, and is especially arranged to operate in a production mode to reduce the data from a deflection survey. This ability is provided by setting up a data base usually consisting of 16 to 27 computed deflection basins calculated by the use of moduli, which span the range of realistic values for each layer, and, also, by the use of the known thicknesses of each layer. The search for the best values of the moduli is conducted using interpolation between the calculated basins; this was found to produce the final results some 30 to 100 times faster than other backcalculation methods employing iterative calculations. It is this speed which makes this procedure practical for use in a production mode of data reduction. The user's manual for MODULUS is contained in Appendix F.

Data collected in a mass inventory survey have uses at the network and project levels. At the network level, the major interest is in having data that can be used for comparing the relative stiffness and remaining life of each section of pavement in the network at the project level. NDT data are used to determine not only the layer moduli at relatively frequent intervals but also the load transfer capability of cracks, the presence of voids between layers, the thermal effects of stabilized layers, the depth to bedrock and water tables, and other important site-specific data that are useful in planning and designing a rehabilitation effort and in providing realistic field data.

All of these uses, whether they are at the network or project level, require that the layer moduli be comparable to each other, that is, that they have either been measured at or corrected to the same conditions of load level, temperature, and loading duration or frequency. The standard condition to which all moduli should be corrected was set in this project to be a design load of 9 kips, moving at highway speeds corresponding to a frequency of 8 Hz, or a pulse duration of 0.0625 sec. These assume a basin width of 10 ft and a travel speed of 55 mph. The temperature to which all moduli should be corrected is 70 °F. Making these corrections to a standard condition recognizes the fact that deflection surveys are conducted throughout the day and over periods of many months. The fact that moisture changes in the base course and subgrade will alter those layers' moduli from season to season also requires an ability to project a reasonable pattern of these changes of moduli throughout the year as part of the process of estimating the remaining life of the pavement.

A major part of the research effort was devoted to developing and verifying methods of making modulus corrections. This required making numerous field measurements in different climatic zones throughout a complete year, measuring deflections and temperatures on the surface and beneath it, and soil moisture suction in the sublayers each month. The backcalculated moduli and the temperature and suction data from all of these tests are provided in Appendix A to this report. These data provide a valuable source of information on load, temperature, and moisture corrections.

As important as the analysis and correction to standard conditions are, of equal importance are the identification and reduction of the errors in making accurate measurements of the moduli. There are two kinds of errors: random and systematic. Random errors are principally measurement errors from the load cells and motion sensors. They may be reduced by repeating the measurement. Systematic errors are more numerous and more difficult to reduce, and include erroneous assumptions made in the backcalculation process. If they are recognized, systematic errors can be corrected, but such correction requires experience. To compensate for the normal user's lack of such detailed experience and to assist in making the layer moduli as accurate as possible, an expert system was developed for use with the backcalculation program and is described in detail in Appendix H. The expert system incorporates most of the rules-of-thumb and systematic procedures that were developed in this project for the correction of moduli and the reduction of the errors in the calculated moduli.

A number of exercises were undertaken to give an estimate of the sizes of error that should be expected. In the field, multiple measurements were made at the same location to determine the size of the random error, and multiple measurements were made along several roads to determine the variability of the layer moduli.

In addition, in cooperation with the Transportation Research Board Committee A2B05, Strength and Deformation Properties of Pavements, a backcalculation exercise was conducted using eight calculated basins in which the moduli were known and seven measured basins in which the moduli were not known. Thirteen agencies in the United States and the United Kingdom participated, each using their own method of backcalculation. The range of errors between the backcalculated moduli and the known values was large, but the differences between the moduli as backcalculated by the agencies from the measured basins was even larger. However, there were four or five agencies that consistently produced small errors with both the calculated and measured basins. What these latter agencies had in common was expertise in guiding the backcalculation process to final values that are closer to the correct or the more likely values. This is why an expert (or an expert system) will be needed in backcalculating the layer moduli of a pavement.

The process can not be viewed as a "black box" into which go raw deflections and out of which emerge acceptable values of layer moduli. The reason for this, as will be discussed in Chapters

Two and Three, is principally in the systematic errors that are made in the measurement and backcalculation process. Simply put, if poor assumptions are made concerning the pavement materials properties and thicknesses, unacceptable results are assured because systematic errors have a multiplying effect. On the other hand, an expert knows how to deal with systematic errors, and knows when "close enough" is indeed close enough. The expert system provided with this report will assist the inexperienced in obtaining consistently acceptable layer moduli.

RESEARCH APPROACH

The following tasks constitute the research approach: (1) selection of nondestructive testing equipment for both network and project level testing; (2) development of an analysis method for use in backcalculation; (3) identification of the sources and sizes of errors in testing and backcalculation; (4) development of methods for correcting the backcalculated results to standard conditions; (5) development of an expert system to assist in reducing random and systematic errors; (6) field data collection for the correction study; (7) laboratory testing for the correction study; (8) correlations between different nondestructive testing devices; and (9) development of a method of making corrections for changes in seasonal moisture conditions. Each of these nine tasks is discussed in the following sections.

Task 1—Nondestructive Testing Equipment and Procedures

A utility decision analysis method was used to select the best nondestructive testing equipment. The factors that were considered and the decision weights given to them are given in Appendix K. Fifteen different devices were rated both for network-level and project-level production testing. No attempt was made to rate these same NDT devices for use in research, although, undoubtedly, the final rankings would be different for that purpose. The falling weight deflectometers were found to have the highest ranking. The least expensive of the Road Raters and the Dynaflect were ranked nearly as high for both project and network levels. As a consequence, this report focuses on the falling weight deflectometer (Dynatest Model 8000) and presents correlations of that device with the Road Rater and the Dynaflect.

Network Level Testing

Network level testing uses NDT results in identifying potential project sites, in determining relative priorities among projects, or in detecting differences of pavement behavior caused by factors such as climatic conditions, traffic patterns, or material types. In network level testing, a much smaller number of tests within a pavement segment are performed as compared with project level testing. The number of tests required depends on the purpose of the testing.

In network level analysis, NDT is often used simply to rank sections as stronger or weaker than other pavements of the same pavement type, which helps to determine the priorities among project sections. The problem always faced in network NDT is one of productivity: how few readings may be taken on each section in order to effectively rank the sections.

In this project, the Spearman's rank correlation technique (*1*) is used in comparing the different rankings. Eight sections of the same type of pavement, each 1 mile long, were used and a large number of falling weight deflectometer (FWD) readings were taken on each of the sections. The ranking of these sections, based on the mean values of the center deflections, was considered as the "actual" ranking. Rankings based on a reduced number of tests were then compared with the "actual" ranking by calculating the Spearman's rank correlation coefficient between the two rankings. In this way, the minimum number of tests is found, which generates a ranking that is still highly correlated with the "actual" ranking. The details of this process are provided in Appendix C.

Project Level Testing

Project level testing uses NDT results in designing maintenance and rehabilitation strategies (for example, overlay) for a given pavement section. Project level testing requires a larger number of tests on a section than that of the network level testing to ensure a reliable design. The number of tests required depends on the desired level of reliability.

In project level analysis, it is often necessary to separate the project length into analysis units that are pavement sections exhibiting statistically homogeneous attributes (cross sections, subgrade support, construction histories) and performance. NDT techniques can help to delineate unit boundaries when accurate historic data are not available. An NDT deflection survey is conducted along the length of a project, with deflections taken at closely spaced intervals, e.g., 50 ft. A computer program based on the cumulative difference method, an analytical procedure recommended by AASHTO (*2*), uses the NDT results to delineate analysis units and is described in Appendix D. The number of units and unit boundaries based on the most intensive testing intervals are then compared with those based on a reduced number of tests to find the minimum number of tests needed to identify analysis units.

Task 2—Analysis

Several analysis methods are available for backcalculating modulus values from deflection data. They include layered elastic and finite element computer programs. Each of these two methods has advantages and disadvantages and these are elaborated on in Chapter Two. Because the finite element method is primarily a research tool, at present, emphasis was placed on use of the layered elastic method in this study.

Task 3—Sources and Levels of Error in Analysis

Error in analysis is the discrepancy between deflections measured with nondestructive testing (NDT) devices and deflections calculated from an analysis method. This discrepancy is made up of two types of errors: systematic and random.

A systematic error is not determined by chance but by bias. An example is the error in assuming that all materials are linearly elastic when, in fact, they are stress-sensitive. Another example is the error introduced by temperature gradients in stabilized layers, the presence of a shallow water table or bedrock layer.

Random error is a result of variability in the measurements and in the pavement layers. Examples of such factors, to name a few, include measurement errors in the load cell and the deflection sensors, distortion of the deflection measurements by passing traffic, variability of the thickness of pavement layers, cracked underlying pavement layers, unstable contact of deflection sensors on the pavement, and variable subgrade conditions.

The accuracy of the results of analysis of NDT deflections depends on minimizing the above two types of errors. Details of these procedures are discussed in Chapter Three.

Task 4—Methods of Correction to Standard Conditions

In most cases, it was found that the nonlinear stress-strain curve of pavement base and subgrade materials, and the temperature and frequency-dependent characteristics of asphaltic concrete, and the effect of temperature gradients on stabilized based course materials must usually be accounted for in the process of reducing to a minimum the systematic errors in the backcalculation process. The Asphalt Institute equation (*4*) for the asphaltic concrete modulus was found to be very useful in making the corrections. The base course and subgrade materials moduli were found to be dependent not only on the state of mechanical stress applied to them but also, not surprisingly, on the state of moisture stress, or suction present in them. It is this latter dependency which provides a direct method for making seasonal moisture and temperature corrections of the moduli measured in these materials.

Corrections for Frequency of Loading, Load Level, Temperature, and Moisture

Backcalculated moduli must be corrected to standard frequency of loading, moisture and temperature levels, and, if the NDT device is incapable of applying a design load level, the moduli must also be corrected to the standard load level. Corrections to standard conditions permit correlations between different NDT devices, and they remove the effects of the environment and testing device conditions that might otherwise obscure actual pavement response. Actual field conditions and deflection data are used in Chapter Two to illustrate the application of the corrections.

Recognition of Unusual Field Conditions

Errors in analysis can occur if there are variable subsurface conditions beneath a pavement, such as shallow hard layers and perched or shallow water tables. Errors can also occur because of unusual conditions within the pavement, such as intermediate layers that are stiffer or softer than the layers above and below them. Unless these unusual conditions can be identified, backcalculated modulus values will be unreliable. Guidelines are given in Chapter Two on appropriate means for identifying unusual conditions as well as suggested methods for idealizing them so that analysis will provide reliable results.

Task 5—Use of An Expert System in Testing, Analysis, and Corrections

The purpose of an expert system is to reduce both random errors and systematic errors. The sizes of the random errors may be estimated by replications of the test, and may be reduced by averaging over several tests, but the sizes of the systematic errors are often confounded and are difficult to estimate. Some of the systematic errors can not be eliminated without using a better analysis method than the currently, widely used layer elastic theory; however, it is possible to reduce some of the systematic errors with a better knowledge of the actual pavement behavior and limitations of the analysis method. The use of an expert system technique provides a means to convey the knowledge and experience possessed by expert analysts to a less-experienced analyst, so that systematic errors are kept to a minimum. The expert system developed in this project is named PASELS. Its user's manual is in Appendix H.

Task 6—Field Data Collection

Deflection, temperature, and moisture data were obtained on a monthly basis on flexible pavements with various thicknesses on 22 sites in four different climatic zones in Texas. Test borings were made at each pavement site in which cores of asphaltic concrete were taken as well as bulk and undisturbed samples of the unbound base and subgrade materials. Descriptions of the pavement layers and subsurface stratigraphy are provided in the boring logs in Appendix A.

Task 7—Laboratory Testing

Selected samples of the subgrade and unbound base materials obtained in the field were subjected to standard AASHTO/ASTM tests, including Atterberg Limits Series and mechanical gradations for Unified Soil classification, and the resilient modulus, using the repeated triaxial test for subgrade and unbound base materials (AASHTO T274) and the repetitive indirect tensile test for asphaltic concrete (ASTM D4123). The test results are provided in Appendix A of this report.

An approximate check was made on the instrumentation for reading the moisture stress or suction in the base course and subgrade by using portions of the samples obtained in the test borings. The test has been described by McKeen (*5*) and is known as the filter paper method. The results of these tests are reported by Scullion et al. (*6*).

Task 8—Correlations of Different NDT Devices

Correlation between different NDT devices has been attempted by many agencies and individual researchers. It has generally been concluded that a satisfactory correlation can be established between the deflections measured by two different NDT devices only when the tests were performed on the same or similar pavement structures. It has been recognized that two pavement sections with the same center deflection can have significantly different structural characteristics (stiffness-thickness combinations). For deflection correlations to be valid between a lower load device to a higher load device, the assumption

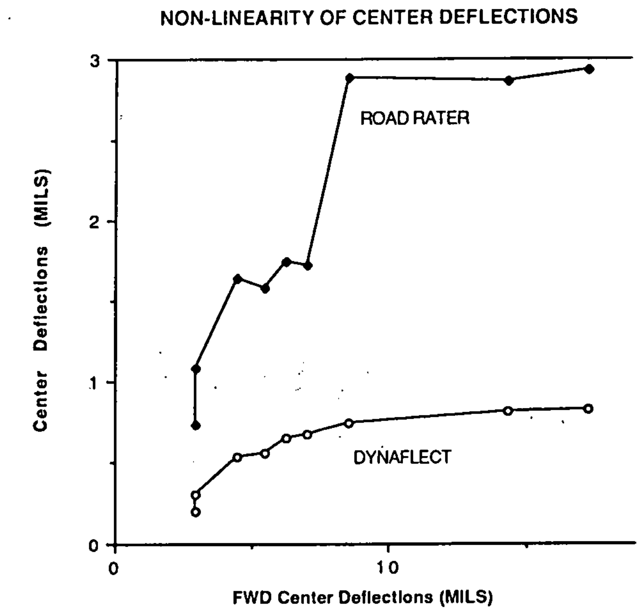


Figure 1. Nonlinearity of center deflections between the Dynatest FWD, the Dynaflect, and the Road Rater.

is made that there is a linear relation between the load applied and deflection measured. In some cases, this may be a reasonable assumption; however, when any nonlinearity develops, the assumption is no longer valid. Figure 1 shows such nonlinearity of pavement response. This figure compares the center deflections measured by FWD, Dynaflect, and Road Rater. The measurements were taken side-by-side on different pavement sections at the TTI pavement testing facilities. The strong nonlinearity of measured deflections between different NDT devices demonstrates that the correlations of NDT deflections are dependent on pavement structures. A better way of establishing correlations between different NDT devices is to correlate the layer moduli after they have been corrected to a common load level, duration, or frequency, temperature and moisture condition. This is demonstrated in Chapter Two.

Factors that affect the correlation of NDT devices include: (1) stress-sensitivity of each structural layer or material within the pavement structure and subgrade, (2) load duration or load frequency, (3) temperature, (4) moisture condition, and (5) loading foot print and contact pressure on the pavement surface.

Procedures to adjust moduli for load levels and load frequencies are presented in Appendix H. Load level adjustments mainly apply to subgrade and base layers, whereas load frequency and temperature adjustments are needed for asphaltic surface layers.

Task 9—Correction for Seasonal Moisture Conditions

The deflection measurements that were made throughout the year at 22 sites in Texas were accompanied by measurements of temperature and soil suction at various depths below the pavement surface. Measurements in the laboratory also included soil suction measurements to tie the field and laboratory measurements together with this important moisture variable. The dependence of the modulus of base and subgrade materials on the soil suction was demonstrated both in theory and in empirical correlations of measurements made in this project and in studies conducted by the Corps of Engineers (*7*). Methods of predicting the change of temperature and soil suction are reviewed in Chapter Two and typical computations of changing soil suction are presented. A method of using this approach to making moisture corrections to the properties of pavement layers, including the modulus and the AASHTO layer coefficients, is described in Chapter Two.

CHAPTER TWO

FINDINGS

INTRODUCTION

This chapter is divided into nine parts. The first part gives an overview of the selection of nondestructive testing equipment and operational guidelines for network level testing and for project level testing. The details of the operational guidelines are contained in Appendixes C and D. The second part gives the findings on analysis methods: how to select them, the advantages and disadvantages of linear elastic and finite element methods, and the sources of random and systematic error in them. The third part describes methods for correcting backcalculated moduli to standard conditions, including load level, temperature, loading frequency or duration, and seasonal moisture changes. The fourth part shows the results of applying the corrections to measurements made on a variety of pavements.

The fifth part discusses and presents the difficulties in backcalculation that are presented by unusual field conditions, such as a shallow hard layer or water table, thin or soft layers, or alternating stiff and soft layers, and the effects of thermal gradients in stabilized layers. This leads naturally to the sixth part, which is a discussion of the need for an expert, or an expert system, in NDT testing, analysis, and reduction of errors, and correction to standard conditions. This section presents the results of the exercise conducted to establish a bench mark of the error levels to be expected from currently used method of backcalculation.

The seventh part demonstrates the correlations that have been developed between different NDT devices; specifically, the falling weight deflectometer, the Road Rater, and the Dynaflect. As expected, the only consistent correlation that could be developed is on the layer moduli backcalculated from the data measured with each device.

The eighth part summarizes the field data that were collected to determine modulus, temperature, and moisture changes throughout the year in a variety of climates. The data base of all field data, including the backcalculated layer moduli, temperature, and moisture suctions, are included in Appendix A.

Finally, the ninth part of this chapter shows a comparison between backcalculated and corrected layer material properties with the results of laboratory tests made on the same materials. Tests were made on asphaltic concrete, base course, and subgrade materials at a variety of stress, temperature, and moisture suction levels. This final part of the chapter demonstrates the results of verifying the material properties measured by NDT and by laboratory methods, and the methods developed in this project for load level, temperature, frequency or load duration, and seasonal moisture variation corrections.

OPERATIONAL GUIDELINES

Selection of NDT Devices and Support Equipment

There are four general types of NDT devices available for pavement evaluations: (1) static deflection, e.g., Benkleman beam; (2) steady-state deflection, e.g., Dynaflect, Road Rater; (3) impulse load deflection, e.g., falling weight deflectometers (FWD); and (4) wave propagation, e.g., spectral analysis of surface waves (SASW) method.

Figure 2 shows a Benkleman beam, and Figure 3 and Figure 4 show a Dynaflect and a Road Rater, respectively. Three FWD devices: a KUAB FWD, a Phoenix FWD, and a Dynatest FWD are shown in Figures 5 to 7.

Inasmuch as the wave propagation devices are still in the development stage, none of them are currently used in production-level data collection. This report will focus on the deflection measurement devices.

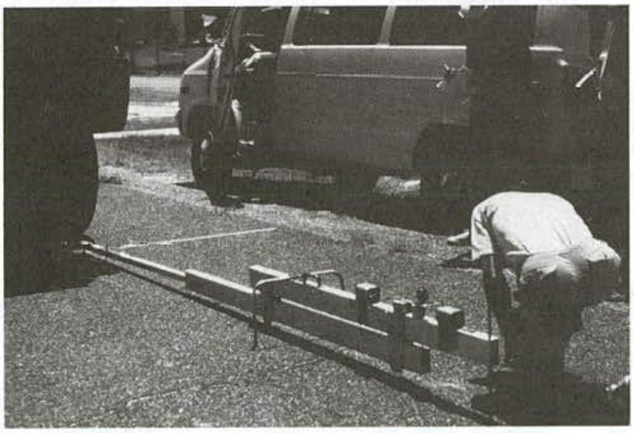


Figure 2. Benkelman beam.

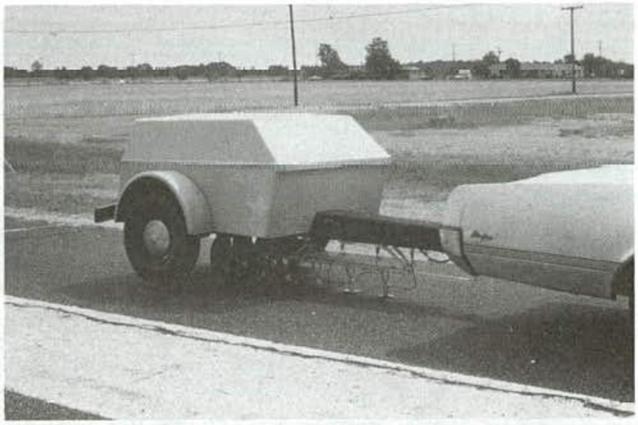


Figure 3. Dynaflect.

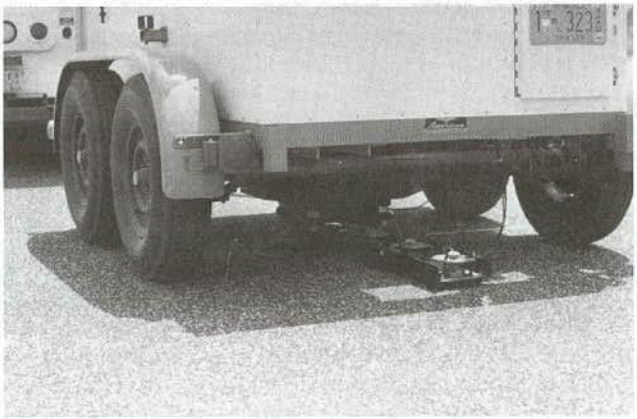


Figure 4. Road Rater.

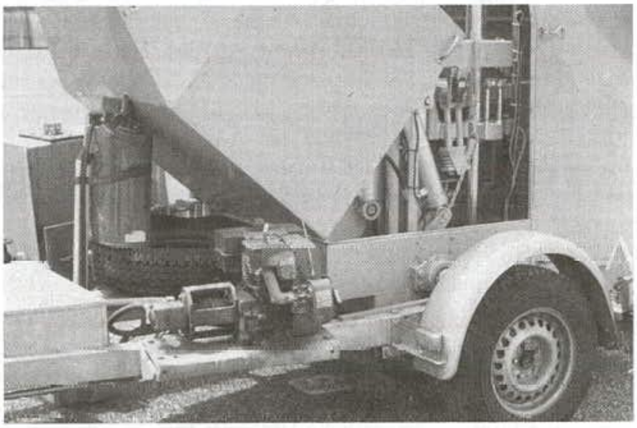


Figure 5. KUAB falling weight deflectometer.

The primary factors that must be considered in the selection of NDT devices include the following: (1) operational characteristics (data collection speed, data recording, traffic delay, calibration requirements, transportability, crew training requirement);

Figure 6. Phoenix falling weight deflectometer.

Figure 7. Dynatest falling weight deflectometer.

(2) data quality (repeatability, suitability, accuracy); (3) cost (annual cost, capital cost); and (4) versatility (number of sensors, range of load levels, movability of sensors). Secondary factors include (1) reliability and (2) time in service.

A detailed description of these criteria is given in Appendix K. Because of their uniformly high rating, the guidelines developed in this report are mainly for the falling weight NDT devices.

Because of the nonlinear behavior of paving materials, and the difficulty in analyzing such behavior, it is preferable for an NDT device to be able to generate loads equivalent to that of the actual design traffic loadings. Since actual traffic loadings vary from light passenger vehicle loads to heavy truck loads, it is desirable for the NDT device to produce variable load levels. The NDT device should be able to produce a maximum load of at least 11,000 lb to simulate the heavier truck loads. The force pulse should approximate the shape of a half-sine wave and have a duration between 20 to 60 msec. In other words, the time elapsed from the onset of loading to the peak value should be in the range of 10 to 30 msec.

Because the number of deflection measurements limits the number of variable modulus layers that can be backcalculated, the NDT device should output at least five deflection measurements. One of them should be the maximum deflection in the center of the loaded area. The next should be as close as possible to the edge of the loaded area. The outermost measurement, which gives the least deflection, should be far enough away from the load to facilitate the pick up of subgrade reactions. Usually, seven measurements with a spacing of 12 in. between each are used. Deflections can be measured by several types of sensors, such as velocity transducers, accelerometers, or seismometers. An on-board microcomputer, which can help to speed up the collection and recording of NDT data, is recommended. If the computer is equipped with 640K RAM, a math coprocessor, and a hard disk, the MODULUS program developed in this project can be used to perform backcalculation during field testing. The MODULUS program is described fully in Appendix F, which contains its user's manual.

Data Collection

In addition to the measured surface deflection data and applied load, other information, such as air temperature, pavement temperature, test point identification, layer thicknesses, layer material type, surface conditions, local topographical features, and drainage conditions, are all useful to the backcalculation. Some of them are required input for backcalculations; the others are needed in interpreting or explaining the backcalculated results.

Before the testing, the test location should be as clean as possible of rocks and debris to ensure that the loading plate and sensors will be properly seated. The device must be calibrated by performing at least two test sequences at the same location and comparing the results. If the difference is greater than 5 percent for any transducer, either the process needs to be repeated until the difference drops below 5 percent or the applied load must be reduced to diminish the effect of permanent deformation.

During the testing, the measured deflection basins need to be examined against any abnormality such as a sensor malfunctioning or improperly resting on the pavement surface. Most FWD devices have an on-board microcomputer that can perform a simple check to see if any of the outer sensors measures a larger deflection than the inner sensors. The operator should be notified of such abnormality to ensure that all the data collected would be useful.

Determination of the Amount of Testing and Test Spacing

Network Level Testing

As indicated in Chapter One, eight farm-to-market road pavement sections, each 1 mile long, were selected. Forty FWD deflection readings were taken on each of the eight sections. A ranking of these sections was determined based on the mean values of the center (maximum) deflections. By skipping every other deflection reading, a reduced sample size of 20 was obtained. Sample sizes of 10, 7, . . . , were obtained in the same manner. Table 1 shows the results of the rankings based on the mean center deflections, W_1, of differing sample sizes.

Depending on the confidence level chosen, the number of tests per pavement section can be found, which gives a ranking that is highly correlated to the actual ranking, which is obtained by doing as many tests as possible. Details of the procedure are given in Appendix C.

In this study, it was concluded that five deflection readings per 1-mile section was the minimum for structural ranking purposes. No matter which deflection characteristic was chosen, maximum deflection, W_1, least deflection, W_7, or surface curvature index ($W_1 - W_2$), the Spearman rank correlation coefficient became unacceptable below five readings per section.

Table 1. Rankings of sections based on FWD center deflections pavement sections and their rankings.

Sample Size	FM785	FM251	FM249	FM323	FM974	FM30588	FM1362	FM3058A	Rs
40	2	4	3	1	6	5	8	7	1.000
20	2	3	4	1	6	5	8	7	.976
10	2	3	4	1	5	7	8	6	.905
7	3	4	2	1	7	5	8	6	.871
5	2	6	3	1	7	5	8	4	.833
4	5	8	1	2	6	3	7	4	.476
2	4	8	1	3	6	5	7	2	.357

Project Level Testing

For project level testing, the objective is to collect data for design purposes. This requires the length of pavement to be divided into homogeneous units, and each unit to be tested a representative number of times. The amount of NDT testing has a direct influence on the accuracy of the estimation of the current pavement condition and the modulus of the surface layer, both of which are major inputs to overlay design. Thus, the amount of NDT testing affects how reliable the design will be, and must be selected, considering the variability of pavement deflections which reflect the variations of subgrade and paving material properties.

Pavement deflection variability is expressed by its coefficient of variation (COV) value, which is defined by COV = $(s / \overline{X})$ 100, where s = variance of the sampled deflections, and $\overline{X}$ = mean of the sampled deflections.

Typical COV values of pavement deflections are as follows: low, 15 percent, average, 30 percent; and high, 45 percent. Low COV values are usually associated with better pavement conditions (stronger), whereas high COV values are associated with poorer and weaker pavement structures.

Depending on the size of the project, the available time and budget, and the purpose of the evaluation, the project level testing interval can vary from 25 ft to 300 ft. For the purpose of overlay design, testing should be performed in each wheel path every 100 to 300 ft. For more detailed analyses, such as detecting localized weak areas, testing should be performed every 25 to 50 ft. Details of the selection process are provided in Appendix D.

ANALYSIS METHODS—LAYERED ELASTIC AND FINITE ELEMENT

Selection of Analysis Methods

Four criteria can be used to select an analysis method: intended use, desired output, speed, and accuracy. Intended use is either for network or project level testing. Desired output is either layer moduli as determined by a layered elastic analysis, or the nonlinear layer moduli used in a finite element analysis. Speed is the time required for the analysis method to compute backcalculated moduli. Accuracy depends on the size of systematic and random errors. A major systematic error is an inappropriate choice of analysis method.

Use of any of the analysis methods presented in this report assumes that dynamic effects are negligible. When the force of an NDT device is first applied to the pavement surface, its action is not transmitted instantaneously to all parts of the pavement section. Stress and deformation waves radiate from the loaded region with finite velocities of propagation. That is, no disturbance occurs at a point in a pavement section until a wave has time to reach it. By assuming that these dynamic effects are negligible, it is assumed that the loading and deflection occur simultaneously. To the degree that this is in error, it is a systematic error that can only be corrected by using dynamic analysis.

In backcalculating moduli or determining stresses and deformations in a pavement section using the computer programs developed in this project, the rate of application of the force is assumed to be low enough that the loading time permits the material to act in the same manner as it does under static loading. It is also assumed that the relations between stress and strain and between load and deflection are essentially the same as those developed for static loading.

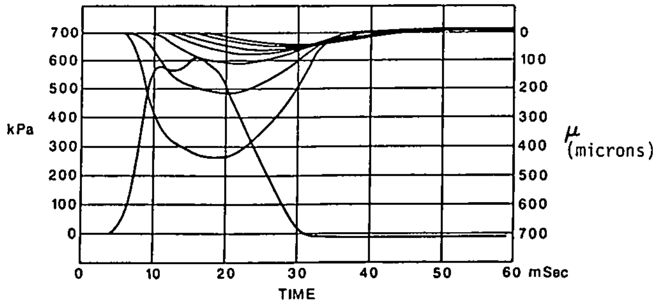
Assessing whether a dynamic or static analysis is appropriate requires knowledge of the velocity at which stress and displacement waves propagate. In the absence of wave velocity data, a review of the load and deflection versus time plots as provided by the Dynatest FWD device can be used as a guide in selecting the appropriate analysis. Such plots are displayed in Figure 8. If the pavement materials are all elastic, the time between the peak load and peak deflection at the outer sensor will be roughly the sensor distance (7 ft) divided by a typical wave velocity (say 2,000 ft/sec), or 3.5 msec. Any time greater than this indicates the presence of material damping and significant dynamic effects in the payment layers. The times between peak load and peak deflection in the last sensor are 16 and 11 msec for sections 10 and 4, respectively. This indicates that dynamic effects are of importance and a static assumption may not be appropriate. The resulting backcalculated moduli may not be representative of the materials of interest.

The foregoing discussion of dynamic and static analysis suggests that backcalculation techniques in the future will probably use dynamic analysis. This report presents static analytical tools for backcalculating moduli that work quite well as will be shown subsequently in this chapter.

Linear Elastic Analysis

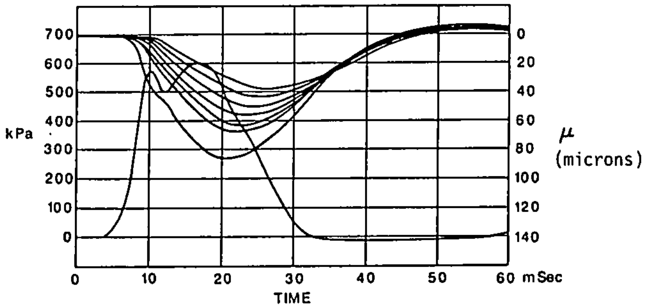
The three main layered linear elastic computer programs from which backcalculation computer programs were developed are CHEVRON, ELSYM-5, and BISAR. BISAR is proprietary and must be obtained by each user from the Shell Oil Company and the other two are in the public domain. Backcalculation computer programs MODULUS and CHEVDEF both utilize CHEVRON, and ELSDEF utilizes ELSYM-5. These backcalculation programs were all considered in this study (*3*).

There are several assumptions on which the linear elastic analysis is based. Limitations are associated with the assumptions



	Peak	@ mSec
kPa	607	15.40
Df1	435	18.63
Df2	214	20.25
Df3	111	21.48
Df4	79	24.30
Df5	65	25.93
Df6	49	28.55
Df7	41	29.38

Section 10 (Soft Pavement)



	Peak	@ mSec
kPa	598	17.00
Df1	87	20.83
Df2	68	22.65
Df3	63	23.68
Df4	56	25.10
Df5	51	24.73
Df6	44	26.55
Df7	38	27.38

Section 4 (Stiff Pavement)

Figure 8. Load/deflection versus time plots from Dynatest FWD at sections 10 and 4, TTI pavement test facility.

and an awareness of them will help to obtain reliable results as well as to explain the outcome of the results. The first assumption is Hooke's Law : stress is proportional to strain in each pavement layer and the proportionality constant is the modulus. Second, each layer is homogeneous and isotropic; moreover, no cracks, voids, or other open spaces are present. Third, the pavement extends infinitely in both the horizontal and vertical directions. Fourth, the pavement surface is free of any stress or strain outside the loaded area of the NDT device. Fifth, the vertical and shearing stresses as well as the vertical and horizontal displacements are continuous across the interface of pavement layers.

Finite Element Analysis

Only one finite element computer program was considered in this study: ILLI-PAVE. This program is comprehensive and can perform analyses on both linear and nonlinear elastic pavement materials. However, selection of appropriate input data for nonlinear analysis requires experience and engineering judgment. Moreover, if the program is operated on a personal computer, even with an appropriate math coprocessor chip, considerable time will be required for the calculations to be performed. The ILLI-PAVE computer program is more suited for main-frame computers, at the present time, and should be considered as a research tool.

The second, fourth, and fifth assumptions given previously for linear layered elastic analysis also apply to finite element analysis. The first assumption also applies when ILLI-PAVE is used in a linear elastic analysis. Assumptions inherent to finite element theory place geometric constraints on the elements and pavement cross section, e.g., the elements should not have length to width ratios exceeding approximately 5 to 1; and the pavement has rigid boundaries at a finite distance horizontally and vertically from the load. This latter restriction is overcome by using a large number of finite elements or by using elastic boundaries.

Interpolation and Search Method

Computer programs CHEVDEF and ELSDEF utilize iteration schemes in conjunction with maximum and minimum bounds for determining modulus values that minimize the error between calculated and measured deflections. These programs can backcalculate reasonable modulus values for conventional flexible pavement sections, i.e., pavement sections having layers that decrease in stiffness with depth. However, they give poor results for pavements having thin asphaltic concrete layers or pavements with intermediate soft or hard layers. An interpolation and search method was developed in lieu of the iteration scheme to improve the results for these types of pavements and to decrease the amount of time to backcalculate moduli. The interpolation and search method is incorporated into the computer program MODULUS.

MODULUS uses the Hooke-Jeeves' pattern search algorithm (*8*) for minimizing the sum of the squared error between calculated and measured deflections. The algorithm is applied to a data base consisting of a large number of calculated deflections and their corresponding squared errors for various predetermined modulus combinations assigned to the pavement layers. Computation of the data base is performed automatically in MODULUS. Once the minimum squared error is determined from the data base by the pattern search algorithm, a 3-point Lagrange interpolation technique is used to compute the associated deflection basin and moduli.

Using an IBM-AT 286 with an 8086 math coprocessor chip, approximately 30 min is required for MODULUS to compute the data base for a four-layer pavement section (conventional, or otherwise); however, once the data base is computed, only 1 to 2 min is required to backcalculate moduli for a given deflection bowl. The data base, moreover, can be used repeatedly for analysis of deflection data obtained at later dates. Because there is a short turn-around time to backcalculate moduli, it is now practical to perform the backcalculation analysis in the field. A field analysis will permit immediate recognition of difficulties in backcalculating moduli, allowing remedial action to be taken on the spot. Typical run times required by various personal computers for generating a data base and performing interpolation as applied to a conventional four-layer pavement system are given in Table 2.

The interpolation and search method can be used with ILLI-

PAVE for the purpose of backcalculating nonlinear material parameters. When the nonlinear material models in ILLI-PAVE are used, there is usually no improvement in the match between calculated and measured deflections over that obtained from linear elastic analysis using MODULUS. Part of this lack of improvement can be explained by representing an infinite domain with a finite number of elements, and by representing the bottom and side boundaries as being rigid. Undoubtedly, increasing the number of elements and using elastic boundaries will enhance the representation, but at the same time significantly increase the computation time. A more important contribution to the lack of improvement is associated with the nonlinear models themselves. Typical nonlinear models used in ILLI-PAVE are presented in Appendix E. Generally, the models relate resilient modulus to either confining pressure, the mean principal stress, or the deviator stress in exponential form and this exponential is, in turn, multiplied by a coefficient:

$$E = K_i[f(\sigma)]^{K_j} \tag{1}$$

where E = resilient modulus; K_i and K_j = material constants, and $f(\sigma)$ = some function of either the mean principal stress, confining pressure, or deviator stress.

Returning now to the use of the interpolation and search method with ILLI-PAVE, an initial determination must be made of which material constants are to be backcalculated. The exponents in the above nonlinear model, Eq. 1, do not generally vary as significantly as do the coefficients with changes in state of stress for a given material. This can be seen in Table E-3 of Appendix E in this report. Based on this observation, the coefficients are the more reasonable of the nonlinear material parameters to be backcalculated. Using ILLI-PAVE, a data base is computed that consists of a large number of calculated deflection basins and their corresponding squared errors for various predetermined coefficient combinations assigned to the appropriate pavement layers. At this point, the interpolation and search method is used to find that set of coefficients from the data base that results in the minimum squared error as was done for the layered linear elastic case. A numerical example of this procedure is presented in Appendix B.

Errors in Analysis

Errors contributing to discrepancy between measured and calculated deflections are numerous but can be identified as either systematic or random, as outlined earlier in Chapter One. Errors usually become of concern when the discrepancy between measured and calculated deflections exceeds the manufacturer's specification for the accuracy of the deflection sensors. For example, the Dynatest FWD (falling weight deflectometer) deflection sensors have an accuracy of approximately ± 2 percent as given by the manufacturer. If the backcalculated moduli result in calculated deflections differing by more than the ± 2 percent tolerance from the measured deflections, the moduli may be questionable and means for reducing the error to within tolerance need to be determined. Remedial measures for systematic errors will be presented first.

Because systematic errors are introduced by bias, their effects may be minimized, if not eliminated, by removing the source of the bias. One type of systematic error has already been discussed regarding the nonlinear models used in the finite element computer program ILLI-PAVE. The remedial measure is to develop a model which more closely matches the response of the nonlinear pavement materials.

Table 2. Run times for data base generation and interpolation in data base using MODULUS.

Data Base Generation

Personal Computer	Run Time
IBM XT	56 minutes
IBM XT with TURBO	35 minutes
IBM 286	18 minutes
IBM 386	7 minutes

Interpolation in Data Base

Personal Computer	Run Time
IBM XT	8 minutes
IBM XT with TURBO	5 minutes
IBM 286	2 minutes
IBM 386	1 minute

A second systematic error is the deviation from the uniform pressure distribution that is assumed by the analysis methods to be applied to the pavement surface through the NDT's loading plate. The uniform pressure assumption is met for pavements having a stiffness comparable to the materials used in the construction of the loading plate. The assumption is violated when a particular pavement has a stiffness much more or much less than the loading plate. The remedial measure is to have loading plates manufactured with different stiffnesses. Alternatively, additional ribbed rubber pads similar to those already attached to the bottom of the loading plates can be attached.

The diameter of the loading plate and the spacing of the deflection sensors in close proximity to the loading plate comprise a third systematic error in the accuracy of the backcalculated modulus of the top pavement layer. The mathematics underlying layered linear elastic analysis show that a reliable modulus for the top pavement layer can be backcalculated when the loading plate's diameter is reduced and the sensors near the loading plate are moved closer to the loading plate. Unfortunately, when this is done the mathematics also show that the modulus values backcalculated for the deeper pavement layers, particularly the subgrade, become less reliable. Observations made during this study indicated that the loading plate of the Dynatest FWD having a diameter of 12 in. resulted in reliable moduli of all the pavement layers for pavements having an asphaltic concrete layer thickness of approximately 3 in. or greater. This suggests the need for a smaller diameter loading plate for pavements having an asphaltic concrete surface layer of less than 3 in.

A fourth systematic error is the validity of the static assumption. Reliable backcalculated moduli were observed to occur when the time intervals between the peak of the load impulse and deflection peaks, as shown in Figure 8, are relatively close. This occurs for stiff pavement sections, i.e., pavements having asphaltic layers 3 in. (7.5 cm), or more, in thickness. In situations where soft pavement sections (pavements having thin asphaltic layers) are encountered, reliable moduli might be backcalculated by ignoring, for example, the deflections at the one or two outermost sensors. By eliminating the outermost sensor(s), the time intervals of the remaining sensors may be of an acceptable amount making the static assumption more acceptable.

A fifth influential systematic error is the presence of significant thermal or suction gradients. Although pavement layers are identified by material type, the presence of such significant gradients could require a layer composed of the same material to be approximately as several layers, each having a different modulus. For example, significant thermal gradients in a 12-in. thick asphaltic concrete layer could require it to be approximated as a 5-in. layer over a 7-in. layer in which the 5-in. layer has a softer modulus than the 7-in. layer because of decreasing temperature with depth. Significant thermal gradients can also cause warping to occur in bound pavement layers.

The presence of thermal or suction gradients in a pavement section can be determined by installing instrumentation for reading these physical quantities or by predicting them from surface temperature and moisture conditions. Thermocouples may be installed for temperature measurements. Suction is a difficult quantity to measure accurately. Several devices are available for this purpose and include tensiometers for wet soils, thermal moisture sensors for wet to slightly wet soils (natural water content wetter than the plastic limit), and thermocouple-psychrometers for slightly wet to very dry soils (natural water content drier than the plastic limit). The tensiometers and thermocouple-psychrometers are relatively reliable, but the thermal moisture sensors are a new technology for measuring suction and recent studies conducted on these sensors by Fredlund et al. (*9*) concluded that further evaluation is required prior to routine field application. Suction is defined and discussed in detail later.

Unlike systematic errors, random errors do not necessarily need to be identified for correction. Random errors are a result of random variations in the pavement or the measurements and the effects of these errors can be reduced by averaging several observations. For example, at any one particular location on the pavement, three or more deflection readings should be made instead of one deflection reading. These deflection readings can then be averaged, or other statistical methods can be applied equally as well, for input into MODULUS. The average of the readings is always more accurate than any single reading unless a reading is affected by other than random error. It is advantageous to identify the random error and the number of readings to be averaged so that an unnecessary amount of time is not used in collecting data.

Probably the most influential random error is the spatial variation of material properties both with depth and length along the roadway. Unless accurate construction records, including geotechnical information, exist for the pavement, test borings should be made, preferably to a depth of 20 ft in the absence of bedrock, at strategic locations. Strategic locations should be determined by topography and soil survey reports.

A second source of random error is the distortion of the deflection measurements by passing traffic. Heavily traveled routes may have to be tested in the very early morning hours or late evening hours if the off-peak hours are still relatively crowded. Consideration may also be given to lane closure adjacent to the lane being tested if the resulting interruption of traffic is minimal.

A third source of random error is the error of measurement of surface deflections by the sensors. A fourth source of random error is the error in measuring the applied load impulse. These last two errors are reduced by repeating the loads and averaging the measurements.

There are other random and systematic errors. The examples given previously and the associated remedial measures should aid the pavement engineer in discerning errors not covered here but peculiar to the engineer's locale.

CORRECTION OF RESULTS TO STANDARD CONDITIONS

Constitutive Equations for Pavement Materials

If stress is linearly proportional to strain, in the absence of thermal effects, the stress-strain relationship is the basis for layered elastic analysis. Real pavement materials differ from this idealized assumption. Actual relationships between stress, strain, time, moisture, and temperature for pavement materials must be approximated by layered elastic moduli that are selected for the appropriate level of stress conditions, load duration or frequency, temperature and moisture levels. The actual relationships between stress, strain, strain-rate, temperature and the fluid-solid composition of a material are known as the constitutive equation of that material. This relationship must be known reasonably well if corrections are to be made accurately and consistently to convert the backcalculated modulus of each pavement layer to standard conditions, in which it can be compared with moduli measured in other places, at other times, or by other NDT equipment.

The constitutive equation for asphaltic concrete that is adopted here was developed by the Asphalt Institute (*4*) and gives the dependence of the modulus of that material on temperature, frequency of loading and the asphalt-aggregate composition of the mixture. No correction for moisture condition is made in this equation, although the modulus of asphaltic concrete is undoubtedly dependent on the level of moisture it contains.

The constitutive equations for base course and subgrade materials show a nonlinear dependence of the modulus on confining pressure, strain level, suction, and temperature. No frequency or duration of load effects is included, although the moduli of these materials are undoubtedly dependent on them but to a lesser extent than is the asphaltic concrete.

The details of the stress-strain constitutive relationships are presented in Appendix E.

Standard Conditions

Standard conditions for frequency of loading, load level, and temperature are defined as 8 Hz, 9,000 lb (40 kN), and 70 °F (21 °C), respectively. The standard moisture condition for fine-grained subgrades is a suction of −45.0 psi (−310 kPa) which roughly corresponds to the plastic limit of fine-grained soils. The standard moisture condition for coarse-grained subgrades and unbound base course materials is a suction of −10 psi (−69 kPa), which corresponds roughly to an optimum moisture content in those materials. Because the modulus of asphaltic concrete is primarily affected by temperature and frequency of loading, a correction to a standard moisture condition is not required in that material.

Corrections to Standard Conditions

Temperature and Frequency Corrections for Asphaltic Concrete

The temperature correction procedure corrects the asphaltic concrete modulus from the mean pavement temperature at which the deflections were measured to the standard temperature. Direct measurements of the mean temperature may be made on site by drilling a small hole, filling it with fluid (oil or water), and reading a thermometer set in the fluid until it becomes stable. While this is practical to do when conducting a detailed project level investigation, it usually requires too much time in a mass inventory deflection survey, which only permits surface temperatures to be measured. In such cases, the temperature correction procedure for pavements having asphaltic concrete layers greater than 2 in. (5 cm) thick follows that recommended by the Asphalt Institute (*10*) to determine the "mean pavement temperature" at the time the deflection measurements are made. This requires the following data to be collected:

1. Location of test site to select a weather station from which air temperature data may be obtained.
2. Date of test to give the dates on which air temperature data must be collected.
3. Maximum and minimum air temperature for the 5 days prior to the date of the deflection testing.
4. Pavement surface temperature measured at the time of the deflection test.
5. Thickness of the asphaltic portion of the pavement.
6. The frequency of loading or the time duration of the load impulse.
7. The percent asphalt cement by weight of the mix.

Items 3, 4, and 5 are used to enter Figure 9, which is Figure XVI-1 in Ref. 10, to determine the temperature at the top, middle, and bottom of the asphalt layer. The average of these three temperatures is considered to be the average temperature of the layer.

A slightly different procedure from that just described is required for pavements having asphaltic concrete layers less than, or equal to, 2 in. (5 cm) thick. Southgate (*11*) reported that pavement temperatures in the top 2 in. (5 cm) of an asphaltic concrete pavement are more directly dependent on the hour of the day and amount of heat absorption than that attributed to item 3. Figures 10 and 11, obtained from Ref. 11., were used in this study to determine the pavement temperature on the underside of a thin asphaltic concrete layer. This temperature and that of the surface are then averaged.

The next item of information required is the frequency of loading. If the loading device applies a cyclic load to the pavement, such as the Dynaflect or Road Rater, the loading frequency is the actual frequency used in the deflection test. If an impulse loading test is used, the loading frequency may be approximated by:

$$f = \frac{1}{2t} \tag{2}$$

where f = the loading frequency, in Hertz, and t = the time duration of the impulse load, in seconds:

The frequency and temperature correction formula given in Eq. 3 is taken from the equation on page 16 of the Asphalt Institute Research Report No. 82-2 (*4*). More specifically, Eq. 3 is a ratio of the corrected modulus at the standard temperature and frequency to the measured or backcalculated modulus under the temperature and frequency at test conditions:

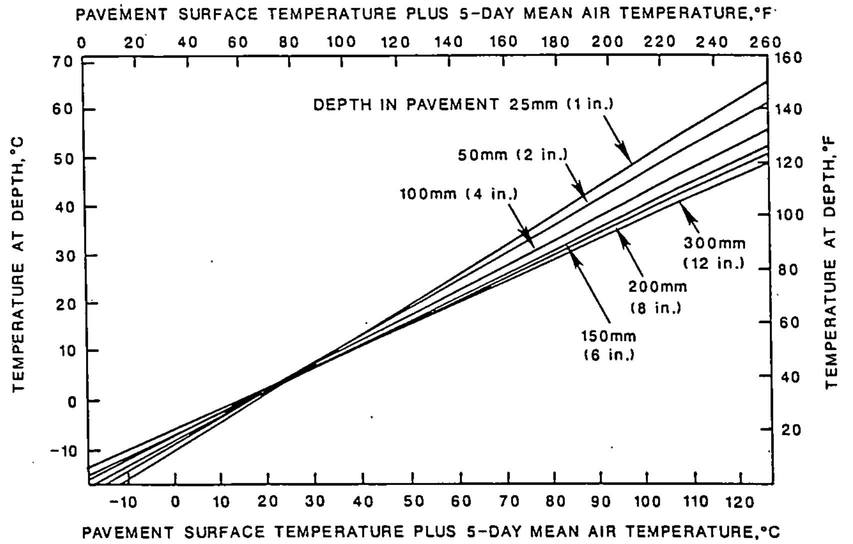


Figure 9. Predicted pavement temperatures, The Asphalt Institute.

$$\text{Log}\, E_o = \log E + 0.028829\, P_{200}\left[\frac{1}{(f_o)^{\ell}} - \frac{1}{(f)^{\ell}}\right] + 0.000005\sqrt{P_{ac}} \times [(t_o)^{r_o} - (t)^{r}] - 0.00189\sqrt{P_{ac}}\left[\frac{(t_o)^{r_o}}{(f_o)^{1.1}} - \frac{(t)^{r}}{(f)^{1.1}}\right] + 0.931757\left[\frac{1}{(f_o)^{n}} - \frac{1}{(f)^{n}}\right] \qquad (3)$$

where: $\ell = 0.17033$; $n = 0.02774$; E = the measured or backcalculated modulus; t, f = the test temperature, °F, and loading frequency, Hertz; t_o, f_o = the standard temperature, 70 °F, and loading frequency, 5 Hertz; P_{ac} = the percent asphalt cement by weight of the mix; E_o = the corrected modulus; $r_o = 1.3 + 0.49825 \log(f_o)$; $r = 1.3 + 0.49825 \log(f)$; and P_{200} = percent aggregate passing No. 200 sieve.

Confirmation of the foregoing correction formula (Eq. 3) was attempted by two methods. One method used was to correct backcalculated asphaltic concrete moduli to the standard conditions. The other method used was to obtain an asphaltic concrete core from the Texas Transportation Institute's pavement test facility (*12*) and determine its moduli at different temperatures for a given frequency. Both methods showed that the equation produces corrected moduli within acceptable levels of error. An appraisal of the results is discussed in detail in Chapter Three.

Temperature and Moisture Correction for Unbound Materials

Field measurements of temperature with depth in selected pavement sections throughout Texas during a period of 1 year for this study have revealed that the modulus of unbound materials is not only affected by temperature but by moisture as well. Chandra et al. (*13*) developed a formula for correcting moduli of unbound materials to standard temperature and moisture (suction) conditions:

$$\Delta E = K_1 K_2\, [\theta]^{u}\left[\frac{x}{\sqrt{2\omega}} + \frac{(1-x)}{4\omega}\right]\left[\frac{\alpha_v \Delta T}{3}\right]^{3/2} + \Delta\psi\theta_v \qquad (4)$$

where:

$u = K_2 - 1$;
$\omega = 3(1 - \nu^2)/(4E)$;
$x = (0.48 - n_{obs})/0.22$;
n_{obs} = porosity;
E = modulus associated with initial temperature and suction;
ΔE = change in modulus resulting from changes in suction and temperature;
ν = Poisson's ratio associated with initial temperature and suction;
α_v = cubical thermal coefficient, which is approximately three times the linear thermal coefficient;
ΔT = initial temperature minus final temperature;
$\Delta\psi$ = initial suction minus final suction;
θ_v = volumetric moisture content;
θ = the mean principal stress; and
K_1, K_2 = material constants.

Note that the quantity ($K_1K_2\,\theta^u$) in Eq. 4 comes from Eq. 1 relating the resilient modulus to the mean principal stresses. Equation 4 is an approximation in view of the assumptions made in its derivation, namely: (1) the cubical thermal coefficient does not change appreciably with changes in temperature; and (2) the volumetric moisture content does not change appreciably with

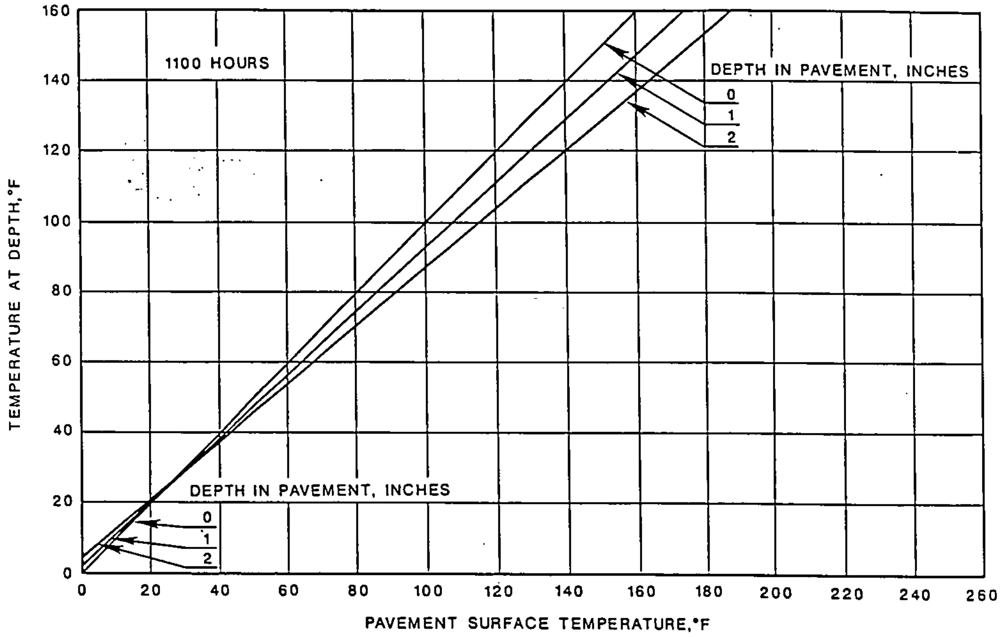


Figure 10. Temperature prediction graphs for pavements equal to or less than 2 inches thick.

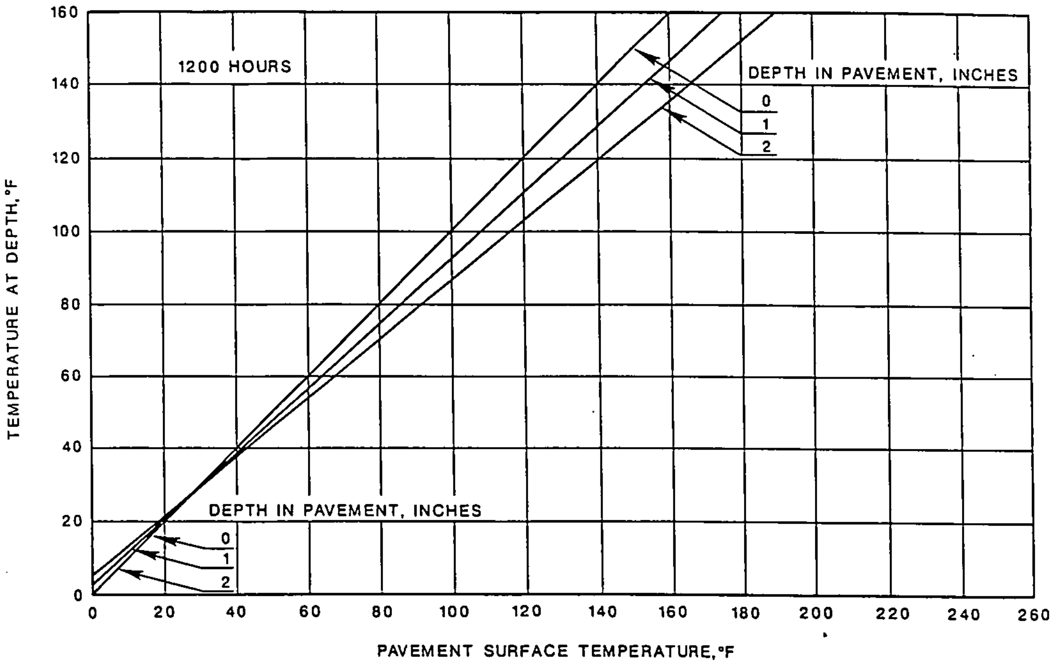


Figure 11. Temperature prediction graphs for pavements equal to or less than 2 inches thick.

changes in suction. If either of these assumptions is questionable, nonlinear representations can be used.

Assumption (1) should be satisfied if the temperature in unbound materials remains above freezing. Assumption (1) is considered to be valid for unbound materials consisting of hard aggregates with small amounts (less than 5 percent passing the U.S. No. 200 sieve by weight) of fine material. Unbound materials with appreciable amounts of fines may experience significant changes in the cubical thermal coefficient in the interval of temperature in which freezing or thawing occurs. Assumption (2) requires a moisture characteristic curve (suction versus volumetric moisture content) to be constructed for the material of interest.

The term "suction" has been used but not defined in the text until this point. It is a term used by soils engineers to describe the state of moisture tension in unsaturated soils. Soil scientists call it "water potential" because it provides the energy head required to drive water through the pores in such soils. Total suction is made up of two parts: osmotic suction due to salts dissolved in the pore water and matrix suction, due to the attraction of water for the surfaces of the soil particles. The total suction is measured by the relative vapor pressure in an unsaturated soil and is defined by the following equation:

$$h = \frac{RT}{mg} \ln \left(\frac{P}{P_o}\right) \qquad (5)$$

where:

h = the total suction in the pore water is gm-cm/gm of water vapor;
R = the universal gas constant, 8.314×10^7 erg/°K-mole;
T = the absolute temperature in °K;
m = the gram-molecular weight of water, 18.02 grams/mole;
g = the acceleration due to gravity, 981cm/sec^2;
P = the vapor pressure of the pore water;
P_o = the saturated vapor pressure; and
$\frac{P}{P_o}$ = the ratio of vapor pressures is the relative humidity.

Suction is a negative number expressed in several equivalent terms, some of which are in terms of head (cm, ft, etc.), the logarithm of the head (pF), and the equivalent hydrostatic pressure (kg/cm^2, kPa, psi, bars). The logarithm of the suction expressed in centimeters is the most commonly used measure of suction: $\mathrm{pF} = \log_{10} |\text{suction in cm}|$. Table 3 gives several equivalent values of suction.

The practical range of suction which will be found in soils in the field is between a pF of 2 and 6. The curve relating the water content of the soil to the suction is a fundamental property of the soil. These moisture characteristic curves can be established

Table 3. Equivalent values of suction.

Suction, cm	Suction, pF	Suction, kPa	Suction, psi	Suction, bars	Soil Moisture Condition
-10	1.0	-0.98	-0.14	-0.0098	Liquid Limit
-100	2.0	-9.81	-0.42	-0.0981	Field Capacity*
-1000	3.0	-98.06	-14.2	-0.9806	
-10,000	4.0	-980.6	-142.2	-9.806	
-100,000	5.0	-9806	-1422	-98.06	
-10^6	6.0	-98,060	-14220	-980.6	Airdry
-10^7	7.0	-980,600	-142,200	-9806	Oven dry

* Field Capacity is the smallest suction normally measured in soils in the field.

in two ways. One way is by laboratory testing, which requires an investment of approximately $5,000 (1986 dollars) in equipment. Another way is by calculating the curves using published regression equations developed by Saxton et al. (*14*) along with particle size analysis data (i.e., mechanical sieve and hydrometer test results). This latter approach is very simple, especially if U. S. Soil Conservation Service soil survey reports are available. Particle size data are included in these reports and can be used to develop a moisture characteristic curve prior to obtaining particle size analysis tests on the subgrade materials.

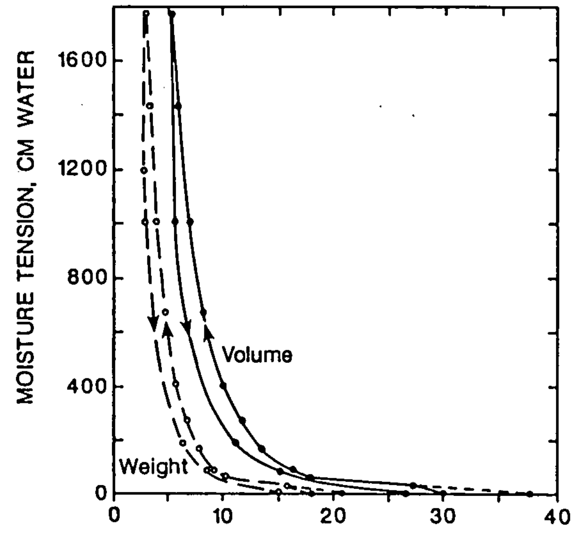


Figure 12(a). Laboratory curves for Hart Brothers Sand (Ref. 15).

Examples of laboratory and calculated moisture characteristic curves are shown in Figures 12(a) and 12(b), respectively.

If the change of volumetric water content is more than 5 percent, the computation of Eq. 4 should proceed in a stepwise manner. The interval between the initial and standard suction values on the moisture characteristic curve should be divided into subintervals so that the percent difference in volumetric moisture content across each step does not exceed 5 percent. The change in modulus for each step is then calculated using Eq. 4 where the volumetric moisture content value to be used in this equation is the volumetric moisture content corresponding to the beginning of the step. The total change in modulus from the initial to the standard water potential is then the sum of all of the modulus changes for each step.

Load Level Correction

If the materials in each pavement layer are in their linear elastic range under the stress conditions caused by both the nondestructive test load and the design traffic load, there is no need to make any correction of the layer moduli for load level. A test of whether the materials in a pavement behave linearly is to determine whether the surface deflections vary linearly with load level, all the way up to the design load level. This test is not conclusive, as will be explained next.

Majidzadeh and Ilves (*16*) have shown that, for an increase in load level, the resilient modulus (a secant modulus) will increase for granular materials and decrease for fine-grained materials. This type of behavior is represented by the coefficients for Eq. 1 for resilient modulus as shown in Table E-3. An understanding of these findings is illustrated in Figure 13. If a granular material (unbound base course) overlies a fine-grained subgrade, an increase in load level from the test load imposed on the pavement during nondestructive testing to the design load will increase the base course's modulus and at the same time decrease the subgrade's modulus. The net result is that the surface deflections

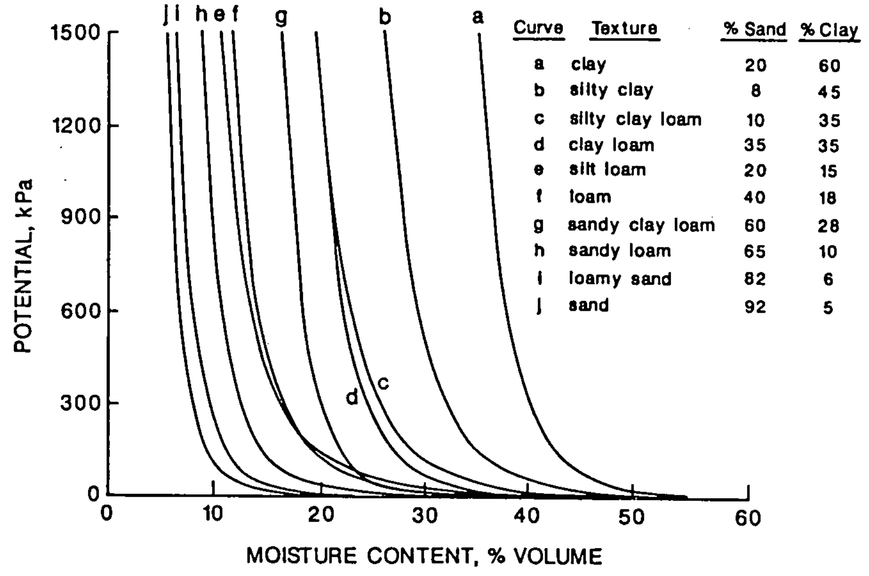


Figure 12(b). Predicted curves for soil class centroid texture (0 to 1,500 kPa range) (Ref. 14).

may be nearly linear with load level. Thus, even if the load-to-deflection ratio is nearly linear with load level, that fact alone does not prove conclusively that the materials in the layers are in their linear range and their moduli need no correction for load level. The procedure to correct a modulus to a standard load level is accomplished through the following formula:

$$\frac{E_k}{E_j} = \frac{E_{ik}}{E_{ij}} \left[\frac{a + \dfrac{(1-a)}{\left[1+\left[\dfrac{(1-a)\epsilon_k}{b}\right]^m\right]^{1/m}}}{a + \dfrac{(1-a)}{\left[1+\left[\dfrac{(1-a)\epsilon_j}{b}\right]^m\right]^{1/m}}} \right] \qquad (6)$$

where:

E_k/E_j = correction factor to be multiplied by the backcalculated moduli to obtain the corrected moduli;
E_k = the resilient modulus (secant modulus) at the standard load level;
E_j = the backcalculated modulus at the load level imposed by the NDT device;
E_{ik} = the initial tangent modulus at the standard load;
E_{ij} = the initial tangent modulus at NDT load level;
a,b,m = dimensionless constants given in Table E-1, Appendix E;
ϵ_k = the strain under the standard load level; and
ϵ_j = the strain under the NDT load level.

Equation 6 is used in an iterative process in which the stresses (θ, σ_3, or σ_d) and strains (ϵ_k and ϵ_j) are calculated both for the standard load level and the NDT load level. The same analysis method used to backcalculate the moduli at the NDT load level should be used to calculate the appropriate stresses and strains (i.e., σ_d, ϵ_k, and ϵ_j). The state of stress as represented by θ and σ_3, are assumed to be geostatic stresses. They are calculated knowing the unit weights and Poisson's ratios of the pavement layers. The stresses and strains are computed at mid-depth in the pavement layers above the subgrade and at 1 ft (30 cm) into the subgrade. Specifics on the manner in which the aforementioned stresses and strains are calculated are given next and in Chapter Three.

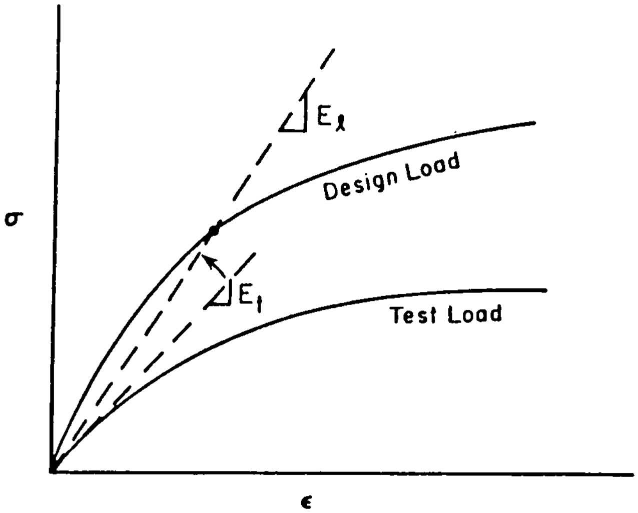


Figure 13(a). Stress-strain curve for a granular base course.

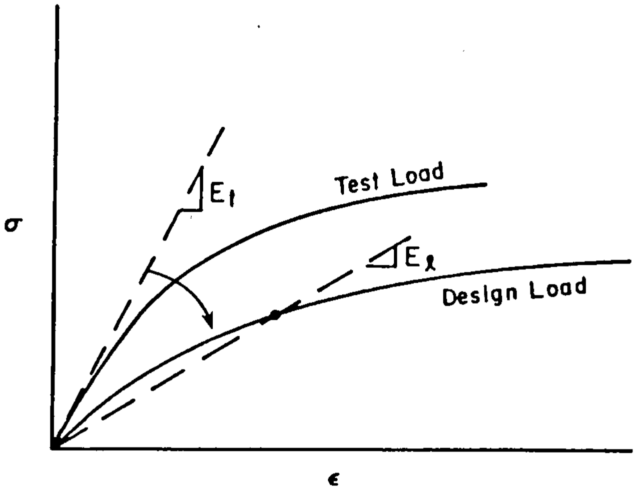


Figure 13(b). Stress-strain curve for a fine-grained subgrade.

The iterative process is initiated by assuming a modulus for each layer under the standard load level. Next, the stresses and strains are calculated for both load levels. The initial tangent moduli, E_{ik} and E_{ij}, are then estimated using the regression equations and material properties given in Table E-3 of Appendix E in this report. Next, the correction factor, E_k/E_j, is calculated for each required pavement layer. The corrected moduli are then obtained by multiplying the backcalculated moduli by the correction factors. A comparison between the corrected moduli and the assumed moduli is made next. If the corrected moduli are significantly different from those assumed, new corrected moduli are determined (using the recently corrected moduli as assumed moduli) until the corrected moduli are sufficiently close to those which were previously calculated. The most recently calculated moduli are the corrected moduli. Convergence of this process is fairly rapid, usually requiring no more than three to five iterations. Application of the above procedure is demonstrated in Chapter Three.

The foregoing procedure for correcting a modulus from one load level to another is an approximation that is based on the assumption that the initial tangent modulus, E_{ik} and E_{ij}, can be estimated from the regression constants for resilient moduli (i.e., secant moduli) given in Table E-3 of Appendix E.

AASHTO Moisture Correction Coefficients

The 1986 AASHTO "Guide for Design of Pavement Structures" (*2*) has incorporated into the structural number (SN) equation the effect of water on the stiffness (strength) of each material through the use of moisture correction coefficients, m_i, otherwise known as *m*-values:

$$SN = a_1 D_1 + a_2 m_2 D_2 + a_3 m_3 D_3 \qquad (7)$$

where SN = structural number, a_i = structural layer coefficients, D_i = layer thicknesses, and m_i = moisture correction coefficients (m-values).

The m-values, as presented in Eq. 7, are only applied to the unbound pavement layers lying above the subgrade and below the asphaltic concrete layer. Although only one procedure was presented in the 1986 AASHTO Guide, Volume 1, (*2*) for selecting m-values, there is another procedure. Equation NN.14 in Appendix NN, Volume 2 of Ref. 2 defines the m-values in terms of moduli:

$$\mathrm{SN} = D_1 a_{1s}\left[\frac{E_{1m}}{E_{1s}}\right]^{1/3} + D_2 a_{2s}\left[\frac{E_{2m}}{E_{2s}}\right]^{1/3} + D_3 a_{3s}\left[\frac{E_{3m}}{E_{3s}}\right]^{1/3} \quad (8)$$

where SN = structural number, a_{is} = structural layer coefficient for the material used in the AASHTO Road Test (chosen as standard), D_i = layer thickness, E_{im} = modulus of the pavement layer under different conditions than at the AASHTO Road Test, and E_{is} = modulus of the AASHTO pavement layer under standard conditions.

A comparison of Eq. NN.14 (Eq. 8) with Eq. 7 indicates that the m-values can be represented by the expression:

$$m_i = \left[\frac{E_{im}}{E_{is}}\right]^{1/3} \quad (9)$$

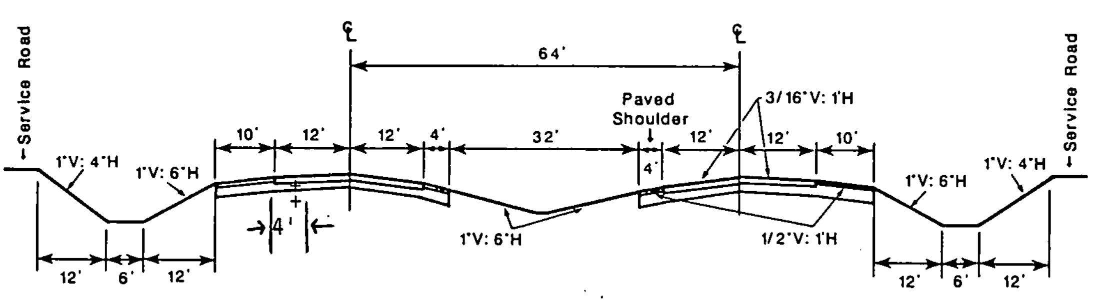
where all the variables were defined previously. The m-values are now easily computed by Eq. 9, with the E_{im} for the unbound materials being the values that the layer will have under local moisture conditions. Note that in Eq. 8 an m-value is applied to the asphaltic layer unlike Eq. 7 where it is not. This m-value should be considered as the effect of the environment on the asphalt stiffness. The m-values on the unbound materials are defined by AASHTO (*2*) to be the effects of water on the stiffness of the unbound materials.

Two different methods can be used to determine an appropriate value of E_{im} for unbound materials. One method is to obtain a laboratory relationship between the resilient modulus and suction. Then, with an estimate of the in-situ suction, the resilient modulus for that suction level is determined. This modulus is then corrected for temperature using Eq. 4 and an estimate of the in-situ temperature. The other method is to backcalculate moduli from deflection data obtained in different seasons throughout the year.

Estimating the in-situ suction can be accomplished by either installing instrumentation (e.g., tensiometers, thermocouple-psychrometers) for reading suction directly, or by calculating suctions from precipitation data provided by the U.S. Weather Service. A computer program was developed for calculating suctions beneath pavements as an aid in designing vertical moisture barriers (*17*). The computer program uses finite elements to solve the diffusion equation which governs moisture flow in partially saturated materials. A user's guide to the program is provided in Appendix I.

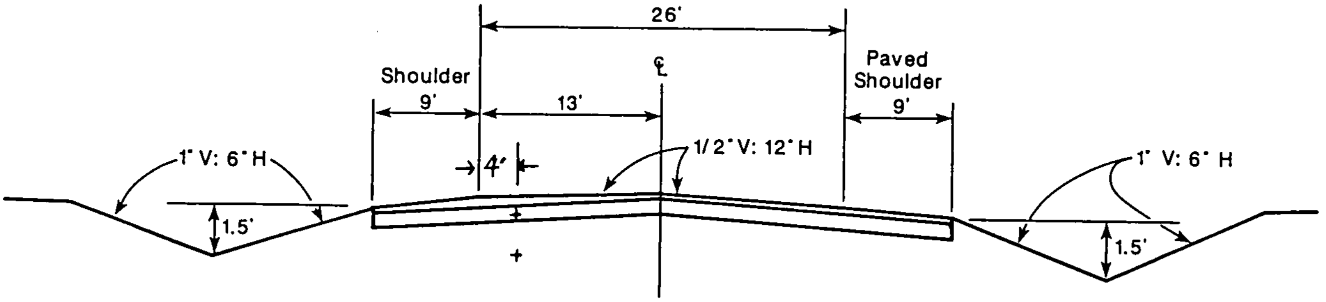
Example results of the calculations made with the computer program for calculating moisture suction are given for sites 8 and 9 near Abilene, Texas, in a dry-freeze climate and site 16 near Lufkin, Texas, in a wet-no freeze climate. The cross section of site 8 is shown in Figure 14, site 9 is a Farm-to-Market road with a 26-ft wide surface treatment on an 8-in. thick crushed limestone base course with an unpaved graded shoulder. The cross section of site 16 is shown in Figure 15. Suctions were measured in the base course and subgrades at each site. Thermocouple psychrometers were placed in sites 8 and 9 because the range of suction within which they are accurate is between a pF of 3.5 and 5.0. Thermal moisture sensors were used in site 16 because the wetter conditions were within the accurate range of these instruments, i.e., between a pF of 0 and 3.5. The instru-

IH-20 M.P. 273 Abilene, Texas (Site 8)



8" Asphalt
13" Limestone Base
Sandy Clay to Clay Subgrade
+ Psychrometers; Depth, 1.5' (Base Course)
and 3.5' (subgrade)

Figure 14. Cross-section of site 8.



8.5" Asphalt Concrete
8.5" Sand Base
72" Sandy Clay
∞ Silty Clay
+ Moisture Sensors; Depth, 1.0' (Base Course)
and 2.5' (subgrade)

Figure 15. Cross-section of site 16.

ments were placed beneath the right wheel path in the center of the base course and 1 ft into the subgrade.

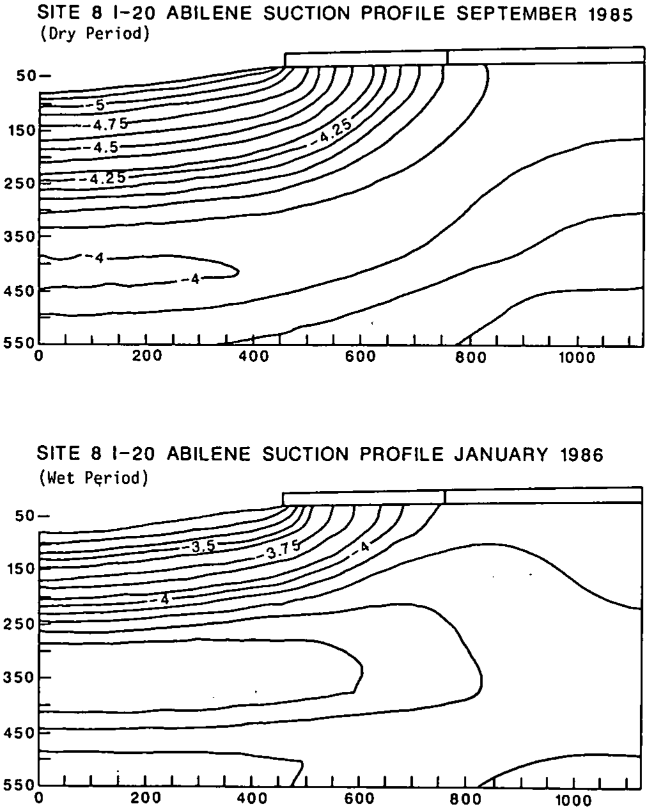
The computer program makes use of monthly rainfall data provided by the U.S. Weather Bureau and marches forward in time calculating the suction in the entire pavement cross section beneath the surface layer of the pavement. Suction contours for the wet and dry periods of the year at site 8 are shown in Figure 16. Suction contours for site 16 during the wet and dry periods are shown in Figure 17. It is apparent from these predictions that the Lufkin, Texas, site (site 16) is in the wetter climate because of the smaller values of suction.

Suction varies with depth throughout the seasons, as shown in Figure 18, at site 8 near Abilene, Texas, and in Figure 19 at site 16 near Lufkin, Texas. There are sharp breaks in the suction profiles at 360 cm (12 ft) of depth at site 8 and at 240 cm (8 ft) of depth at site 16, both indicating a change from a coarser grained to a finer grained soil at those depths.

The measured suctions are compared with the calculated suctions in Figures 20 and 21. The suction in the subgrade at site 8 is shown in Figure 20. The psychrometer readings less than a pF of 3.0 and more than a pF of 5.0 are unreliable. The remaining readings are generally within acceptable accuracy of the predicted values. No comparison is made of the suction in the base course because the psychrometer was nonoperative.

The measured and calculated suctions in both the base course and subgrade at site 9 are compared in Figures 21 (base course) and 22 (subgrade). Once more, the measurements near and more than a pF of 5.0 are unreliable, whereas the remaining measurements generally confirm the predicted trends. The suction measurements in the subgrade match the predicted values unusually well.

The suctions measured by the thermal moisture sensors at site 16 and illustrated in Figures 23 and 24 reflect the long equilibration time required when these sensors are installed in a saturated condition. Not until March of 1988 did these sensors begin to respond to seasonal fluctuations of moisture suction. After that date, the sensor in the base course indicated a drying trend and then a sharp return to a wet condition around a pF of 2.4. In the subgrade, the moisture sensor measurements followed the predicted pattern of suction very well. All measurements are within the sensitive range of the moisture sensor.


SITE 8 I-20 ABILENE SUCTION PROFILE SEPTEMBER 1985
(Dry Period)

SITE 8 I-20 ABILENE SUCTION PROFILE JANUARY 1986
(Wet Period)

Figure 16. Water potential calculations for dry and wet periods of the year at site 8.

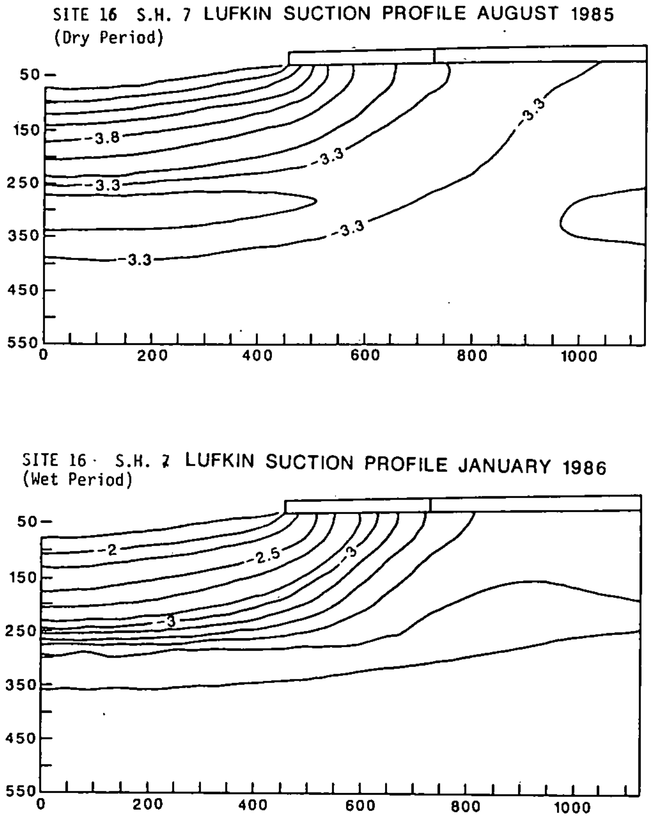


Figure 17. Water potential calculations for dry and wet periods of the year at site 16.

This comparison of the measured with the calculated suctions demonstrates several important points: (1) suctions can be measured in the field with different instruments that have been selected for their proper operating range; (2) measured suctions can be matched reasonably well with predicted suctions; and (3) the consequent changes in base course and subgrade moduli because of changes in moisture suction can be predicted and thus moisture corrections can be made on a rational predictable basis.

An estimate of the temperature at any location in the pavement can be obtained by one of two ways. One way is to instrument the pavement section with thermocouples. The second way is to compute the temperature using the computer program CMS (*18*) or the recently developed Integrated Model (*19*). The input to CMS requires weather data tapes, which can be obtained from the U.S. Weather Bureau. The Integrated Model requires much simpler information as input, namely monthly rainfall and temperature data, and runs on a microcomputer.

RESULTS OF APPLYING CORRECTIONS

Actual Distribution of Moduli Under Load

The actual distribution of moduli within a pavement section under load cannot really be known precisely for two reasons: no instruments exist which measure modulus, and even if there were, random measurement errors would introduce uncertainty in the results. However, from laboratory test data, it is possible to obtain a fairly good understanding of the manner or trend in which moduli respond to various load levels. Results from laboratory tests on various soils indicate that moduli in granular materials will decrease with decreasing stress, whereas moduli in fine-grained materials will increase with decreasing stress. These trends are depicted in Figure 25. Superimposed on the effects of load level are the effects of suction and temperature.

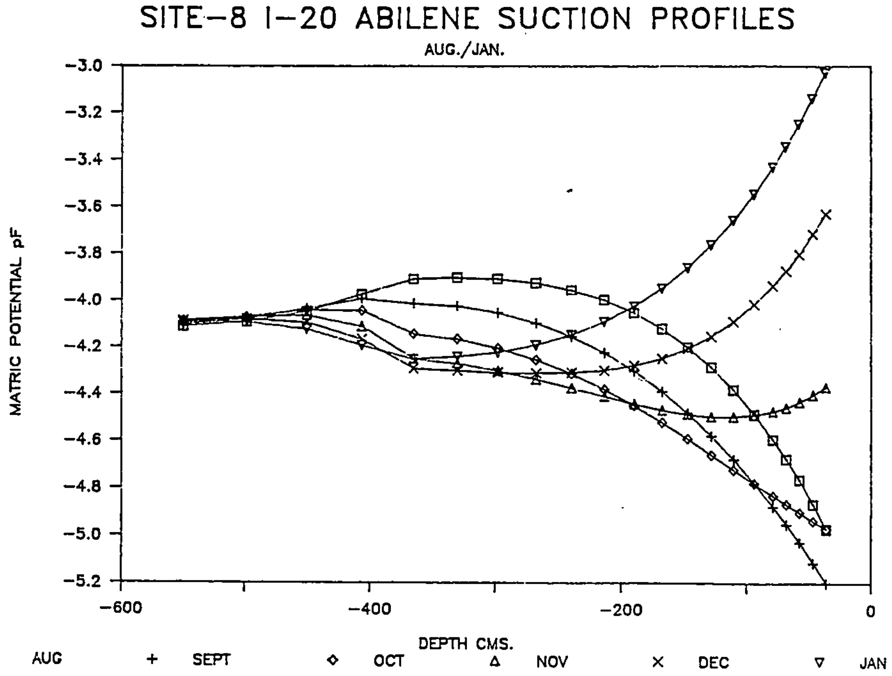


Figure 18. Calculated suction profiles beneath the right wheelpath at site 8.

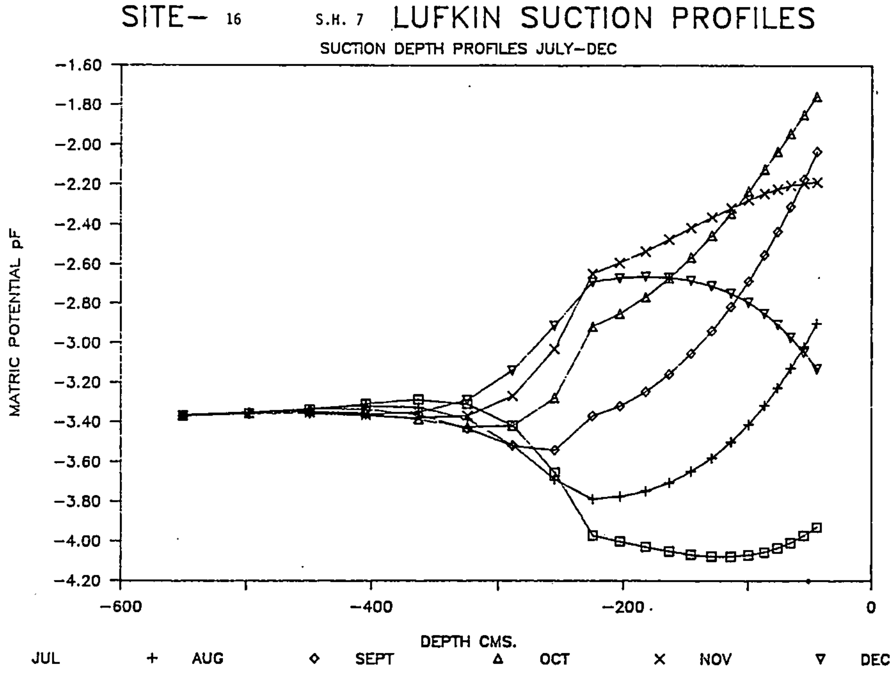


Figure 19. Calculated suction profiles beneath the right wheelpath at site 16.

Generally, for the range of suctions encountered in the field, the more negative the suctions (drier the material), the higher will be the modulus. For temperatures above freezing, the higher the temperature, the higher will be the modulus provided that the pavement layers remain in contact with each other (i.e., no warping).

In regards to asphaltic concrete, the modulus of this material is affected more by the rate of loading and temperature than by the level of load. In this respect, the asphaltic concrete modulus for a given rate of loading should be nearly constant throughout the vertical and horizontal extent of the asphaltic concrete layer.

Linear Elastic and Multiple Layer Linear Elastic

In view of the manner in which the moduli respond to various load levels for stress dependent materials, it is technically incorrect to use a single modulus to characterize an entire layer. Nonetheless, it is common practice to do so with layered linear elastic analysis methods. The single layer modulus that is determined by these methods should be considered as an "average" modulus which produces a calculated deflection basin that is reasonably close to what was measured.

Minimizing the error between the measured and calculated

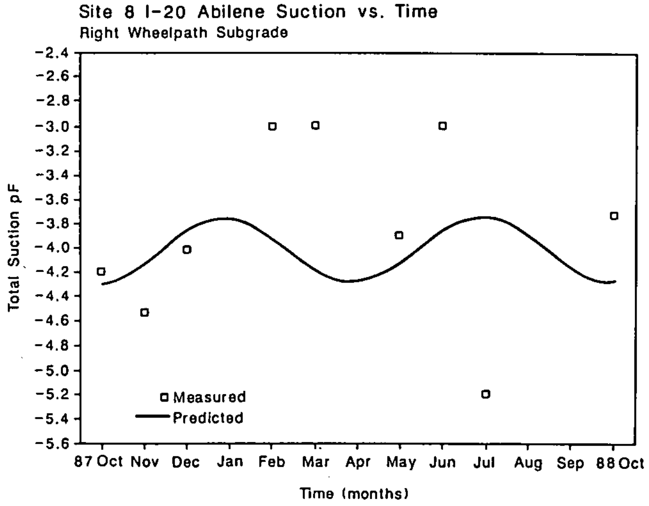


Figure 20. Comparison of calculated and psychrometer-measured suctions in subgrade at site 8.

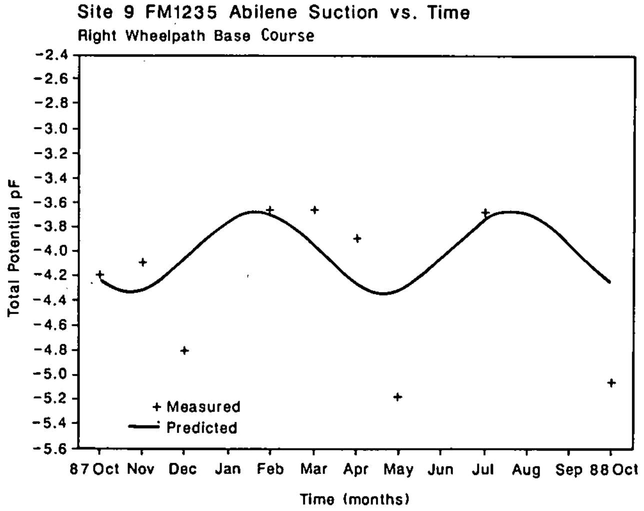


Figure 21. Comparison of calculated and psychrometer-measured suctions in base course at site 9.

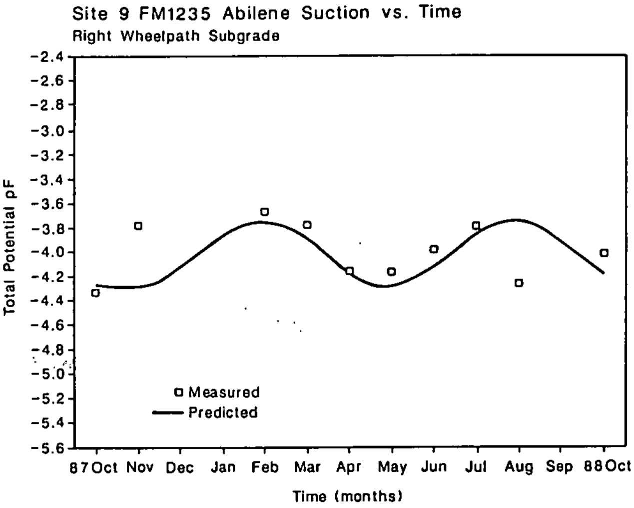


Figure 22. Comparison of calculated and measured suctions in subgrade at site 9.

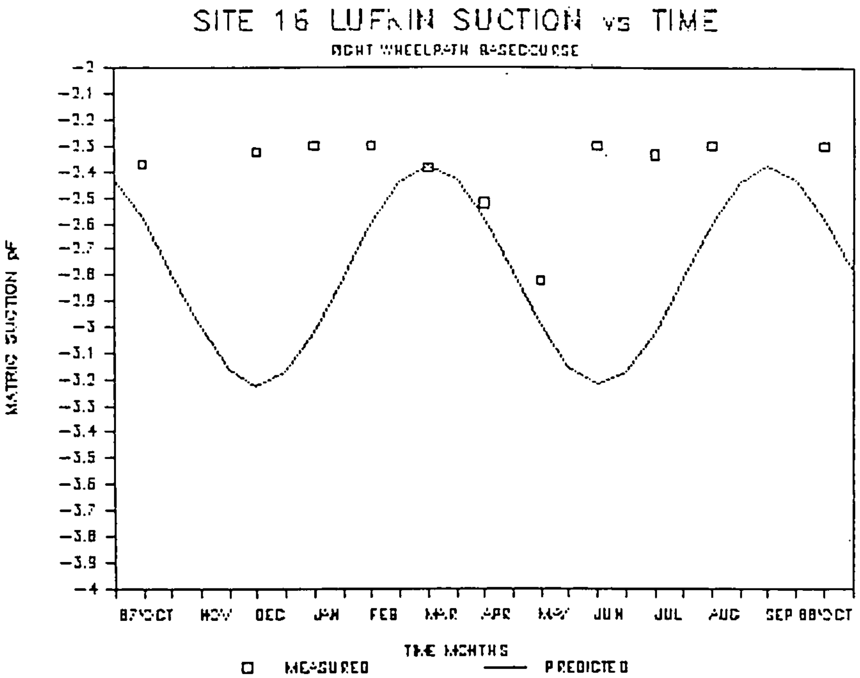


Figure 23. Comparison of calculated and thermal moisture sensor measured suctions in base course at site 16.

deflections to within the manufacturer's specification for the deflection sensors while achieving realistic values of the layer moduli is the desired goal of any backcalculation analysis method. If the error is within the manufacturer's specification for a layered elastic analysis, and the layer moduli are within reasonable expected ranges, the backcalculated moduli should be considered as the best moduli that the analysis and NDT device can produce. If the moduli are not reasonable, this indicates that a systematic error is present in the backcalculation process which can be removed only by the intervention of an expert or an expert system. If the error is not within the manufacturer's specification, especially after attempting to minimize the systematic and random errors, two options should be considered. One option is to rerun the deflection test at other load levels. The second option is to perform a multiple layer linear elastic analysis. Each of these options is discussed in detail below.

Sometimes by increasing or decreasing the load applied to the pavement by the NDT device an acceptable match between calculated and measured deflections will result. The applied load should be increased when the measured deflections using geophones are quite small, e.g., any sensor measuring a deflection of 1 mil (25 microns) or less. The applied load should be decreased when the measured deflections are large, e.g., when the sensor at or closest to the center of the loading plate records a deflection of 50 mils or larger.

In those situations in which the measured deflections are small, the geophones are inaccurate. Increasing the applied load will increase the magnitude of the deflections resulting in more accurate geophone readings. In those situations in which the measured deflections are large, the geophones again have questionable accuracy, and probably of greater consequence, the pavement layers exhibit more nonlinearity and the dynamic effects of the pavement section are influential.

The multiple layer linear elastic analysis requires the pavement section to be divided into additional layers. The idea behind this is to more accurately model the stress dependency of the granular and fine-grained materials. As an example, consider a pavement of 3 in. (4.5 cm) of asphaltic concrete over 16 in. (40 cm) of crushed limestone base material which, in turn, overlies a clay subgrade extending to an infinite depth. On a first trial, the pavement section is modeled as a three-layered system using the actual thicknesses of the pavement layers and the error between

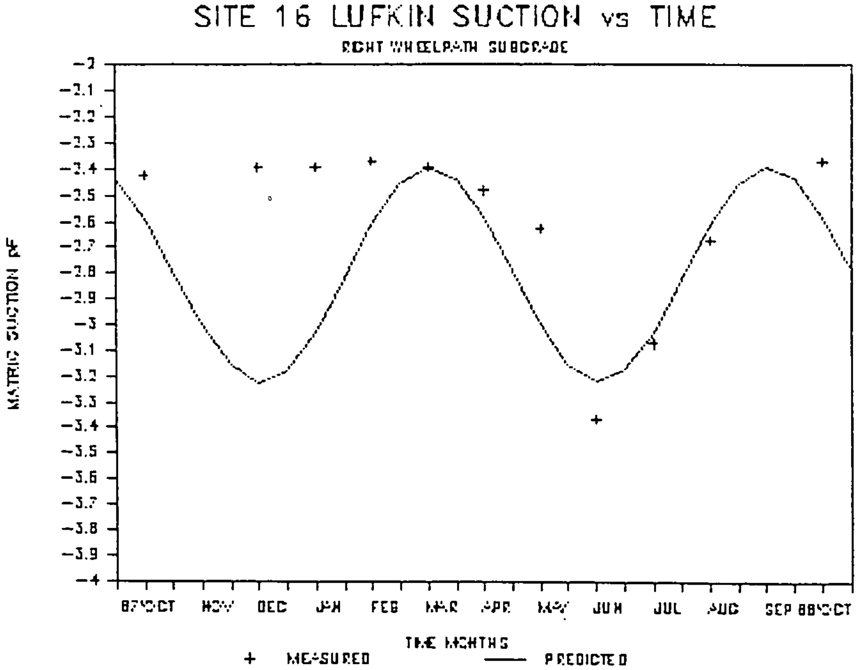


Figure 24. Comparison of calculated and thermal moisture sensor measured suctions in subgrade at site 16.

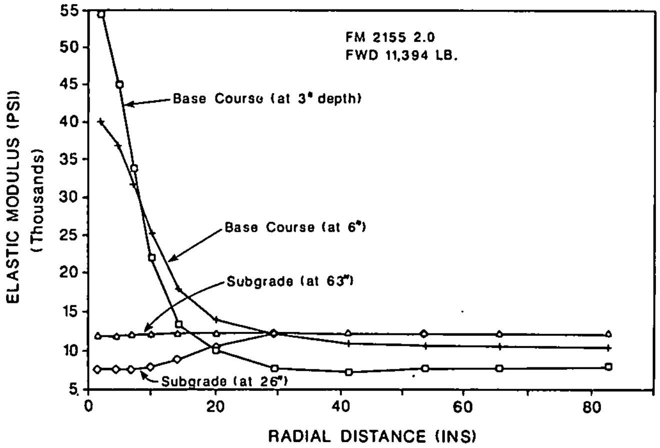


Figure 25. Nonlinear elastic modulus profiles from ILLI-PAVE (20) (1 in. = 2.54 cm; 1 psi = 6.895 kPa).

the calculated and measured deflections is found to be unacceptable. More specifically, the error is observed to be primarily associated with the sensors located at 0 in., 12 in. (30 cm), and 24 in. (60 cm) from the center of the loading plate. Seven sensors, spaced 12 in. (30 cm) apart from each other, were used on the NDT device. The manner in which the error is distributed among the seven sensors suggests that the difficulty lies with the base course and possibly with the asphaltic concrete layer, as well.

As a second trial, the pavement section is modeled as a four-layered system in which the base course is divided into two equal layers. The new backcalculated moduli result in an acceptable error between the measured and calculated deflections. However, more often than not, the backcalculated modulus of the third layer (bottom half of the 16-in. thick base course) will be lower than the backcalculated modulus of the subgrade. The reason for this, which appears at first to be contrary to common knowledge, is that the modulus decreases in each layer with depth because of the stress sensitivity of the base and subgrade materials. A further increase of applied load will increase the modulus of the third layer above that of the subgrade.

Application of the multiple layer linear elastic method will not necessarily result in an acceptable error between calculated and measured deflections. Although it may be true that a very acceptable error can be achieved by dividing the various pavement layers as delineated by material types into additional layers, the time required to backcalculate the moduli for the additional layers becomes exceedingly large.

Finite Element

Theoretically, the only method which can approach an accurate determination of the modulus of a material under a standard load is the finite element method, which adjusts the stiffness of each element in accordance with its own stress state. The finite element method recognizes that the "modulus" of a nonlinear material is not something that is characteristic of a layer but, instead, pertains to a material point within that layer. However, one major drawback of the finite element method is that it is limited to solving finite domain problems as was discussed earlier in this chapter. In other words, as normally constituted, the finite element method cannot handle either a subgrade extending infinitely with depth or a pavement layer extending infinitely in the horizontal direction. It is expected that including elastic boundary conditions in finite element programs will improve this deficiency.

EFFECTS OF UNUSUAL FIELD CONDITIONS

Shallow Hard Layer

A shallow hard layer has been found from field observations to be a layer that is less than 30 ft (9.1 m) from the surface and is stiffer than any of the overlying layers.

A pavement section with a shallow hard layer will exhibit small deflections from an NDT device. A large load imparted by the NDT device should be used to obtain deflections that the geophone sensors can accurately measure.

Depending on how shallow the hard layer is, it may be advisable to ignore the outer sensors (e.g., sensors 5, 6, and 7) and not input their deflections into the selected analysis computer program in order to obtain reasonable backcalculated moduli. This treatment is more applicable to the layered linear elastic analysis (MODULUS) than to the finite element analysis (ILLI-PAVE). The outer sensors may be used to determine approximately the depth of the hard layer. A procedure for doing this was developed by Ullidtz (*21*). Irrespective of the analysis method used, the number of layers modeled in the pavement section should not exceed the number of deflection sensors for which deflection measurements are used as input.

Water Table

The presence of water decreases the modulus of an unbound material. If a water table is present in a layer composed of the same material, it is prudent to divide the layer into two layers, one layer below and the other above the water table. Such a division of layers may not need to be made in those instances where the water table is located at depths greater than the distance from the load to the outermost sensors of the NDT device.

Intermediate Hard and Soft Pavement Layers

The presence of intermediate hard or soft layers approximately 4 in. (10 cm), or more, in thickness do not inhibit backcalculating reliable moduli, especially when using MODULUS. This is particularly true if the thickness and depth of the layer are known.

The presence of a hard layer tends to distribute the applied load resulting in smaller deflection readings. As was noted for shallow hard layers, the NDT device should impart a large enough load to the pavement so that the resulting deflections are sufficiently large for the geophones' readings to be of acceptable accuracy.

The presence of an intermediate soft layer will deform much more than adjacent layers. This results in large deflections at those sensor locations affected by the layer's presence. These large deflections may exceed the sensor's measuring capability requiring lighter loads to be applied by the NDT device.

NEED FOR AN EXPERT SYSTEM

Because of the various errors that may be introduced during the collection and analysis of NDT data, experience with and knowledge of the NDT device and the pavement behavior is necessary to successfully analyze NDT results. A comparative study was carried out by submitting 26 sets of NDT pavement deflection data along with their thickness and material information to participating pavement research agencies around the United States and in Britain. These agencies were asked to report their backcalculation results. A total of 13 results were obtained with varying degrees of completeness. Among the 13 results, ten used surface deflection solutions based on the theory of elasticity and the other three used solutions based on the layer equivalency concept. The results of the study are in Appendix G.

The backcalculation results show a wide dissimilarity among different agencies. Agencies using the same backcalculation program produced considerably different backcalculated moduli values. This can be attributed to the various degrees of experience and differing assumptions used by the individual analysts. Such inconsistency of backcalculation results demonstrates why the analysis of NDT data is very difficult for practicing pavement engineers. Unlike researchers, practicing engineers usually do not have the time and resources to experiment with the many possible assumptions that may change the backcalculation results. An expert system that assembles the knowledge of expert analysts to assist in backcalculation can be very useful.

A prototype expert system named PASELS (for Pavement Structural Evaluation System) which is based on expertise in backcalculating pavement layer moduli is included as one of the analysis methods developed in this project. A complete description and user's guide to PASELS is in Appendix H. The knowledge contained in the PASELS expert system includes:

1. The general knowledge of the properties of paving materials, e.g. the possible range of modulus values and Poisson ratios of particular types of material, the degree of nonlinearity (stress dependency), the effect of temperature on asphalt layer modulus, and the effect of moisture on base and subgrade moduli.
2. The general knowledge of the pavement structures, such as the degree of variation of layer thicknesses due to construction practice and the possible depth to bedrock according to local topography.
3. The knowledge of pavement behavior, e.g., the deflections under or closer to the load are influenced more by the upper layer modulus while the deflections at greater distances away from the load are affected more by the subgrade modulus; moduli of thin layers usually have very a small influence to the surface deflection; a soft layer under a much stiffer layer (e.g., flexible subbase under a cement stabilized base) often has its effect on the surface deflections masked by the stiffer layer; and stabilized layers may have warping induced by temperature gradient.
4. The knowledge of the backcalculation computer program, i.e., the sensitivity of input parameters, assumptions and limitations of the mathematical model, accuracy of the numerical solution of the model, and the accuracy and sensitivity of the numerical search scheme.
5. The knowledge of the sources and approximate sizes of the errors introduced due to instrumentation, due to the discrepancy between the model and reality, and due to the search scheme.
6. The knowledge of the variability of the paving material properties.

The above information is stored in the knowledge base in the form of IF ⟨condition⟩ THEN ⟨action⟩ rules. This rule base not only contains rules-of-thumb but can simulate the reasoning of human experts. The system is written in CLIPS (*22*), an expert systems shell developed by NASA, and uses forward chaining as its main control strategy. PASELS currently employs the backcalculation program MODULUS to compute layer moduli but is able to analyze results from other backcalculation procedures, or more sophisticated analytical models, e.g., nonlinear elastic or finite element methods.

CORRELATION OF DIFFERENT NDT DEVICES

Selection of Correlation Level

The direct correlation of measured deflections between different NDT devices has been shown to be dependent on the pavement structure. Correlations of deflections developed from one pavement structure should not be applied to other pavements except those with the same, or a similar structure and located in the same area.

The only correlation of NDT devices that is independent of pavement structure is that which is based on backcalculated layer moduli. This type of correlation produces reasonably good results, particularly for the subgrade and base layers. The correlations of backcalculated surface layer moduli are not as good because of the size of errors contained in the backcalculated values. Because empirical equations (Eq. 4) based on temperature, asphalt content, aggregate type, and other factors can provide estimates of realistic ranges of asphalt layer moduli, their results should be used in the correlation.

Correlations Developed

Nine pavement sections at the TTI pavement testing facilities were selected and tested by different NDT devices. These test sections were carefully constructed with various combinations of layer materials and layer thicknesses. Within each test section, a selected location was marked so that different NDT devices could be run on the same pavement point with a minimum amount of error caused by spatial variation.

The layer moduli were backcalculated for the nine TTI test sections using MODULUS. Three distinct sets of moduli were obtained from deflections of the three NDT devices: Dynatest FWD, Dynaflect, and Road Rater. The appropriate adjustment procedures were applied. The resulting subgrade and base layer moduli have very good linear correlations among the three devices, as shown in Figures 26 to 28. However, the asphaltic surface layer moduli correlate poorly even after the adjustment. The reason for this is that the backcalculated surface layer moduli contain much larger systematic and random errors than that of other layers. The causes and possible ways of reducing these errors (such as using empirical estimations to adjust the calculated moduli in a backcalculation expert system) are addressed in Chapter Three of this report.

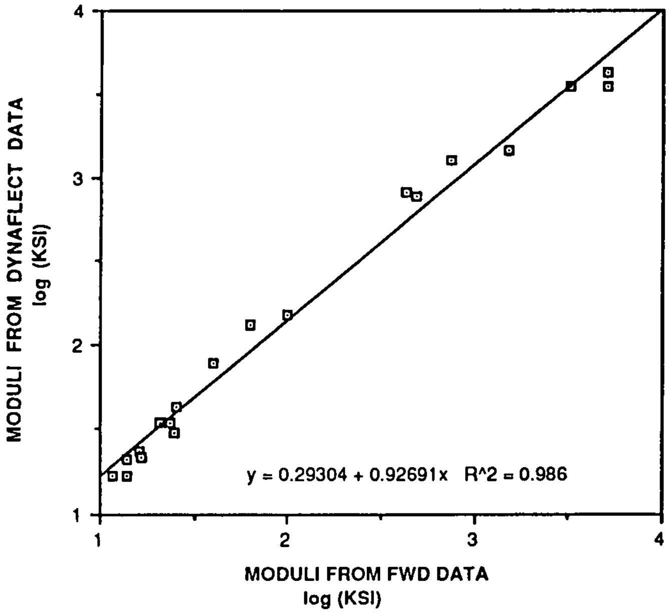


Figure 27. Correlation of backcalculated moduli between FWD and Dynaflect.

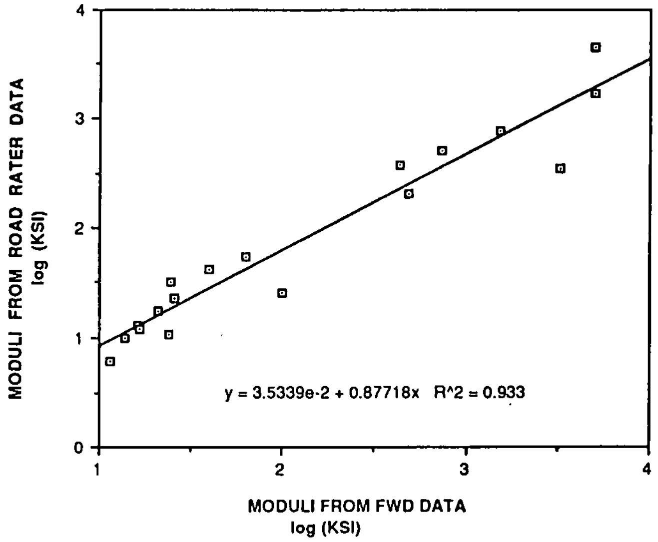


Figure 26. Correlation of backcalculated moduli between FWD and Road Rater.

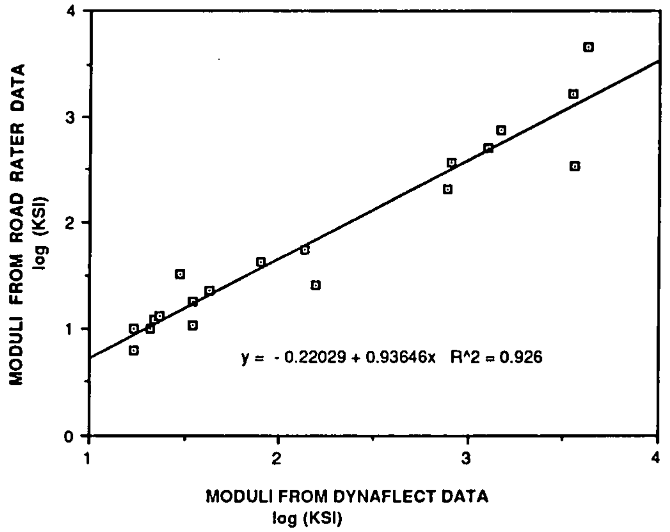


Figure 28. Correlation of backcalculated moduli between Dynaflect and Road Rater.

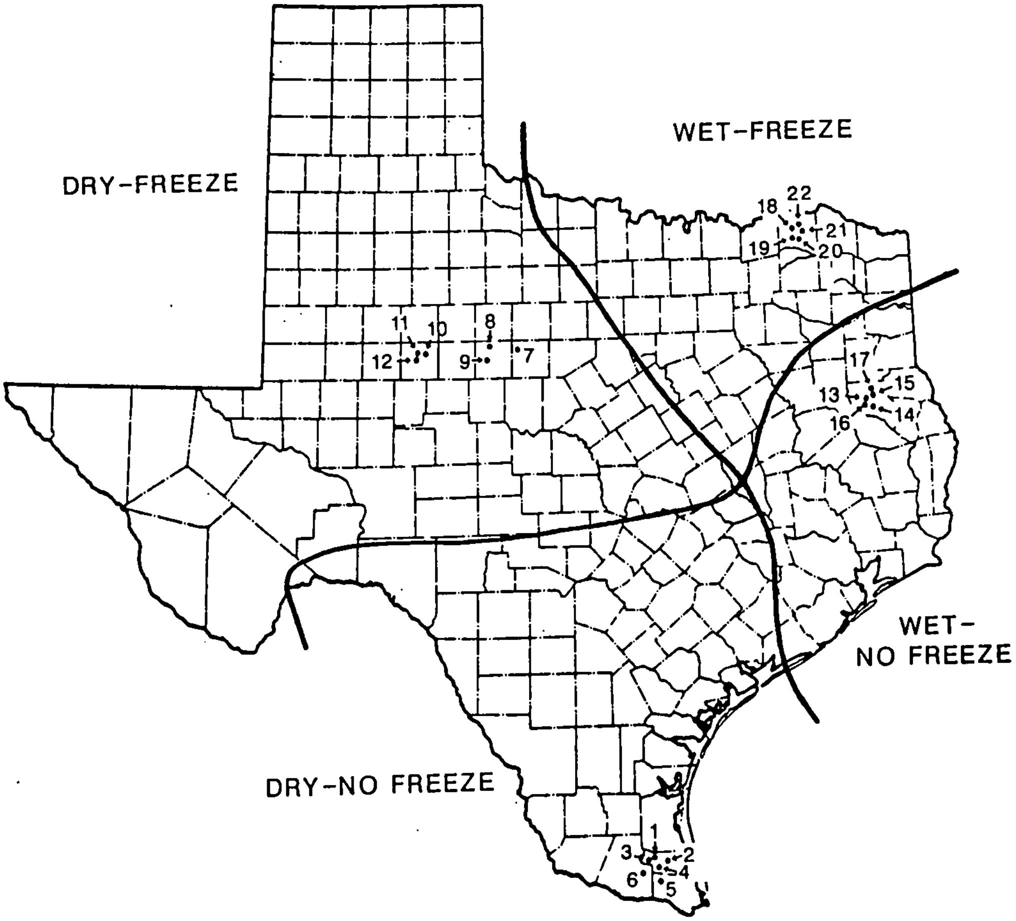


Figure 29. Climatic and site location map.

FIELD DATA COLLECTED

A total of 22 in-service pavements located in Texas were monitored for a period of approximately 1 year. The data included deflections from the Dynatest FWD, suction measurements typically in the base and subgrade, and temperatures at the surface and beneath the asphaltic concrete layer and at some sites at intermediate depths of up to 4 ft (120 cm).

The 22 pavements are divided into four groups, with each group consisting of 4 to 6 pavements, and each group located in a different climatic zone. The four climatic zones are: (1) wet-freeze, (2) wet-no freeze, (3) dry-freeze, and (4) dry-no freeze, as depicted on Figure 29. Each of the 22 pavements was identified by a site number. A list of the 22 pavements giving their site number, route, and Texas SDHPT District is presented in Appendix A.

At each pavement site, ten points, 10 ft (3 m) apart, were located in the outside wheel path. These points marked the locations where deflection data were obtained on a monthly basis. The instrumentation for collecting temperature and suction was typically located at the fourth point. The data collected from this instrumentation was assumed to be representative along the 100 ft (30 m) length. Trends and patterns observed in the data collected are described below.

Seasonal Deflection Patterns With Climate

As anticipated, the deflections were noted to increase as the pavement materials became wetter (i.e., smaller values of suction) or became warmer. Generally, the deflections of the inner sensors, that is, those sensors affected by the asphaltic concrete and base course layers, appeared to be more influenced by temperature changes than the deflections of those sensors affected by the underlying layers.

Seasonal Temperature Patterns With Climate

The following trends were noted in all four climatic zones. Temperature gradients in the different pavement layers, especially in the asphaltic concrete layer, generally were more pronounced in the summer afternoon hours than in other seasons or times of day. The gradients decreased with depth. The summer morning temperature gradients were small in the various pavement layers. In the winter months, the pavement temperatures are fairly uniform with depth; but, in the afternoon, gradients developed, depending on the amount of sunlight available.

Seasonal Moisture Patterns With Climate

Seasonal fluctuations in moisture were more pronounced in the dry than in the wet climates. Examples of each are provided in Figure 30 and Figure 31. Water potentials were difficult to measure in the wet climates mainly because of the type of instrumentation used. Unfortunately, no other technology is available for adequately measuring the range of water potentials typically found in the wet climates, which are between 0 bars and approximately 5 bars of suction.

Seasonal Modulus Patterns With Climate

In order to identify seasonal modulus patterns, care must be taken in selecting appropriate deflection data. Selection is determined when the error between the calculated and measured deflections is less than or equal to the acceptable accuracy of the deflection sensors, e.g., ± 2 percent for the geophone sensors used on the Dynatest FWD. Modulus values backcalculated from deflection data not meeting this criterion are generally unreliable. Moreover, it is important that the same location on

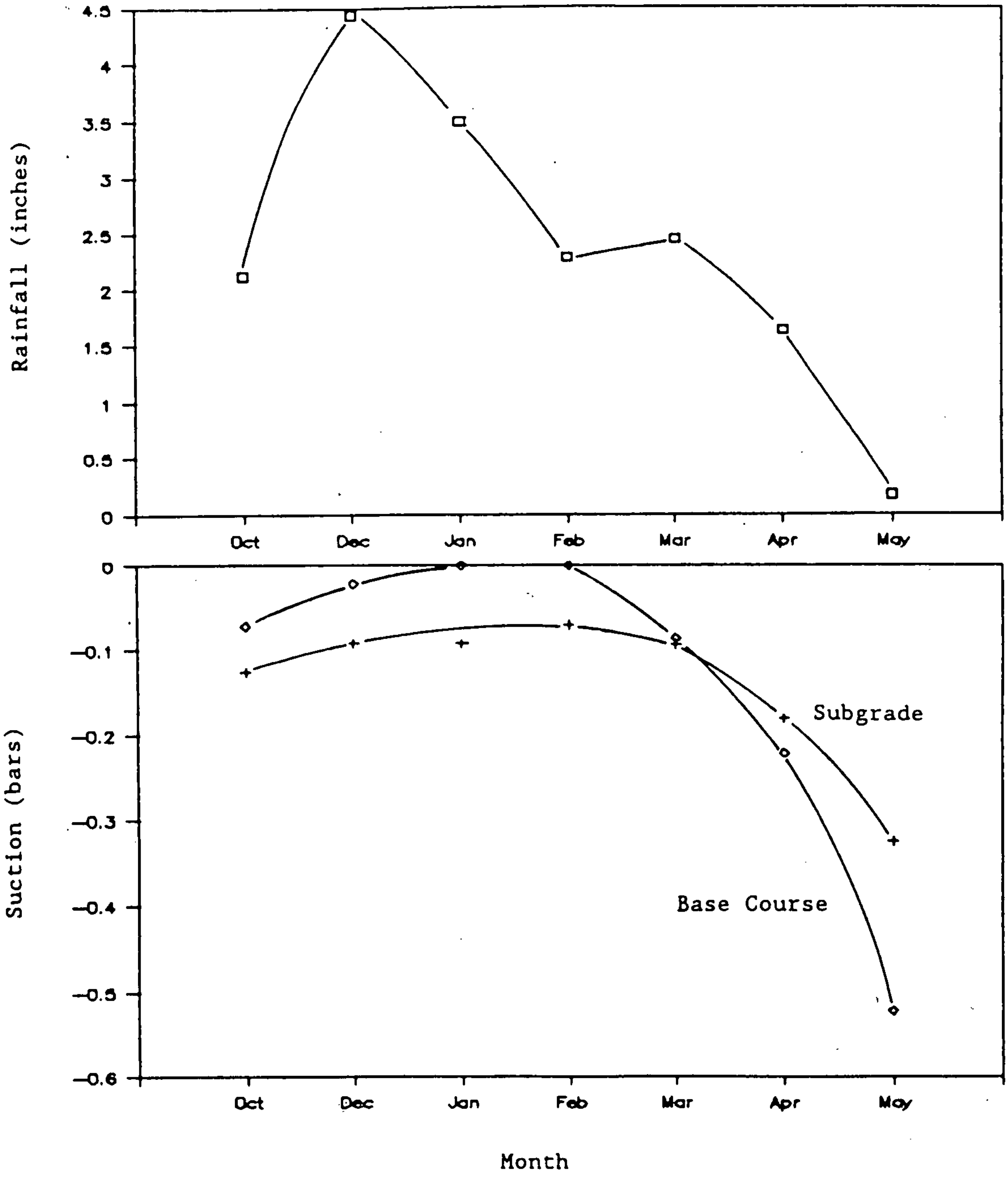


Figure 30. Variation of rainfall and suction of SH7.

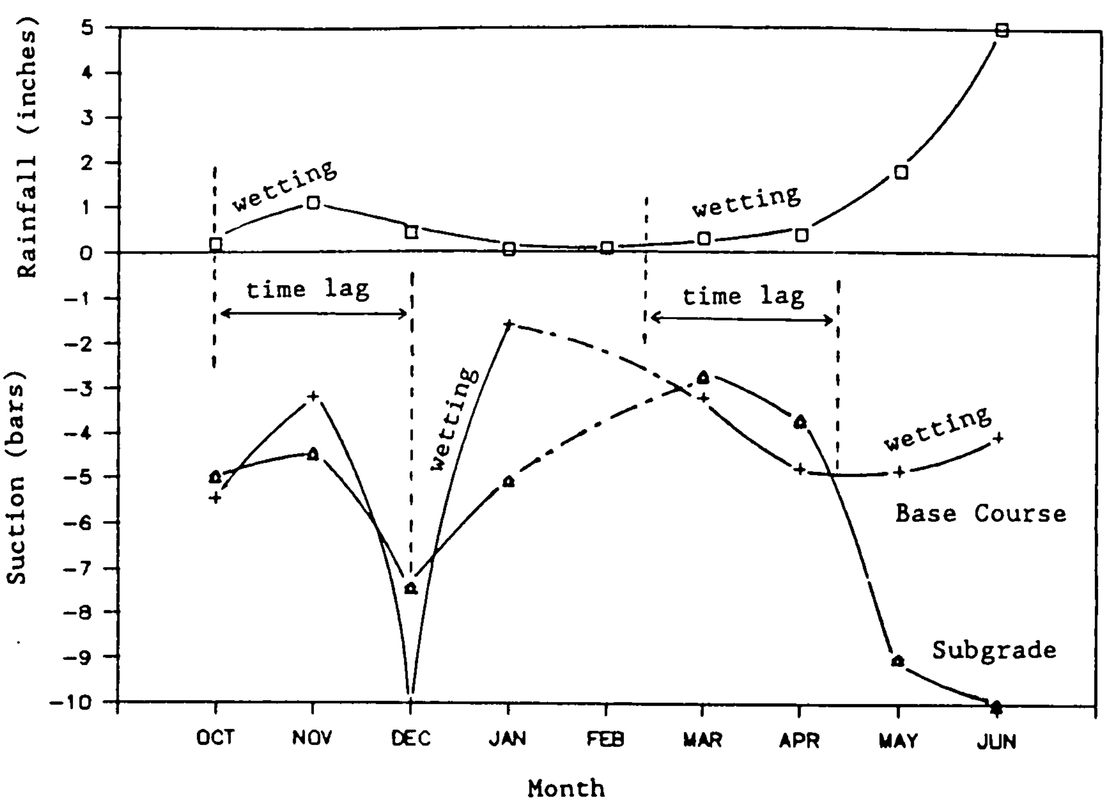


Figure 31. Variation of rainfall and suction at site 9 (dry, freeze climate).

the pavement be used throughout the period that the data are being collected.

Regardless of the climate in which the deflection data were collected, the seasonal changes in moduli were more pronounced in those pavement layers at or near the surface. Subgrade moduli, and subbase moduli to a lesser degree, were somewhat invariant to seasonal effects. These observations are illustrated in Figure 32 for sites 1, 8, and 20, which shows the range of modulus values for each pavement layer over a period of approximately 1 year. The moduli for the asphaltic concrete layers and unbound pavement materials as well as for the subgrade were noted to experience the same response found in laboratory tests. A typical response of backcalculated (field) and laboratory asphaltic concrete moduli to temperature is depicted in Figure 33.

COMPARISON OF LAYER MATERIAL PROPERTIES WITH LABORATORY TEST

Results

The backcalculated moduli were determined from the layered linear elastic computer program MODULUS. The laboratory determined moduli are resilient moduli. Laboratory moduli for the asphaltic concrete samples were determined in accordance with the repeated-load indirect tensile test (ASTM D4123). Laboratory moduli for the unbound pavement and subgrade materials were determined by Scullion et al. (*6*) in accordance with AASHTO T274. Only the asphaltic concrete laboratory results are presented in this report. The laboratory moduli results for the pavement materials other than the asphaltic concrete at each of the 22 pavement sites is given in Ref. 6 and are summarized in Appendix A.

As was described earlier, the deflection data were obtained at ten locations, 10 ft (3 m) apart, along the outer wheel of the outside lane at each of the 22 pavement sites in Texas. Additionally, a test hole in which a core of the asphaltic concrete, bulk samples of granular materials, and Shelby tube samples of fine-grained materials were obtained was drilled approximately at the fourth location from the point of beginning (i.e., approximately 40 ft (12 m) from the point of beginning). Laboratory test results performed on the samples were considered representative of the ten locations.

Asphaltic Concrete

The laboratory and backcalculated moduli for the asphaltic concrete were found to be in close agreement, as shown in Appendix A. This is remarkable because, in layered linear elastic theory, the uppermost layer is the most difficult layer to obtain a modulus. An additional review of Appendix A and Figure 34 indicates that in some instances the asphaltic concrete moduli appear to be stress sensitive. This is especially noted when the asphaltic concrete is of medium thickness, approximately 4 in. (10 cm) thick. An appraisal of the accuracy achieved is given in detail in Chapter Three.

Base Course

The base course is stress sensitive; therefore, in order to compare backcalculated and laboratory moduli, the stress state in

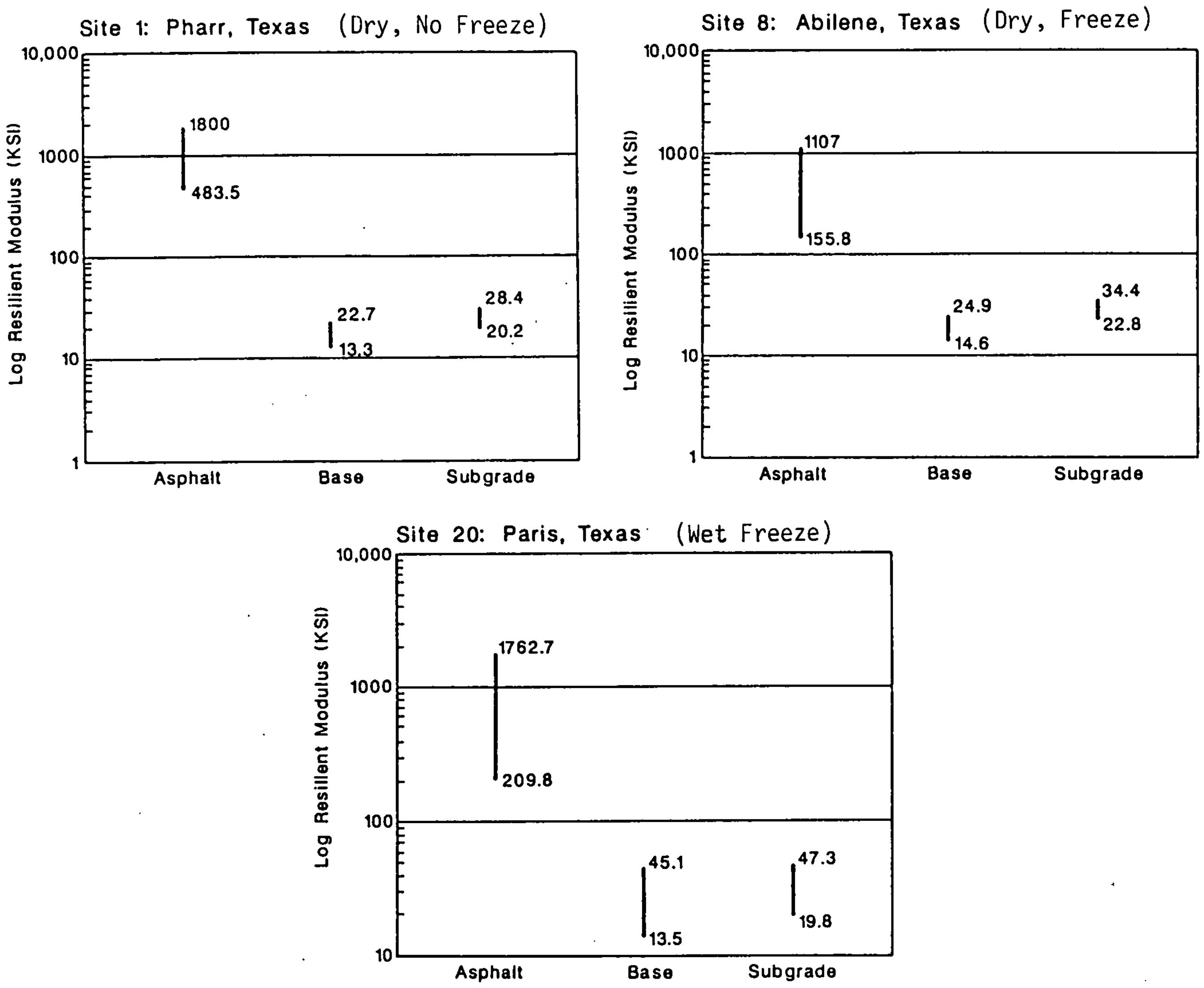


Figure 32. Representative ranges of modulus values for asphaltic, base, and subgrade materials.

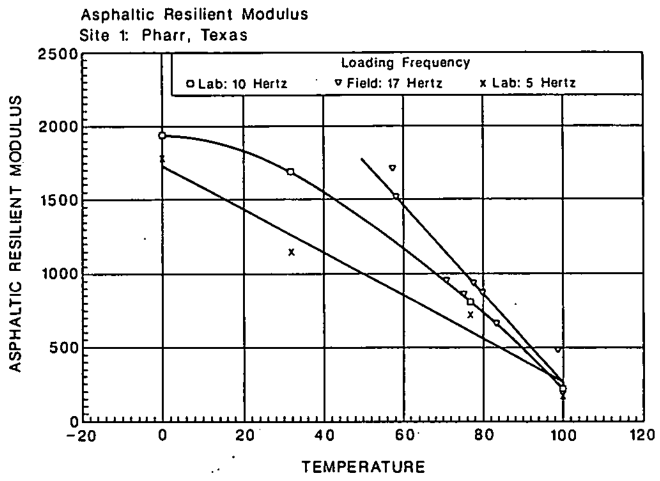
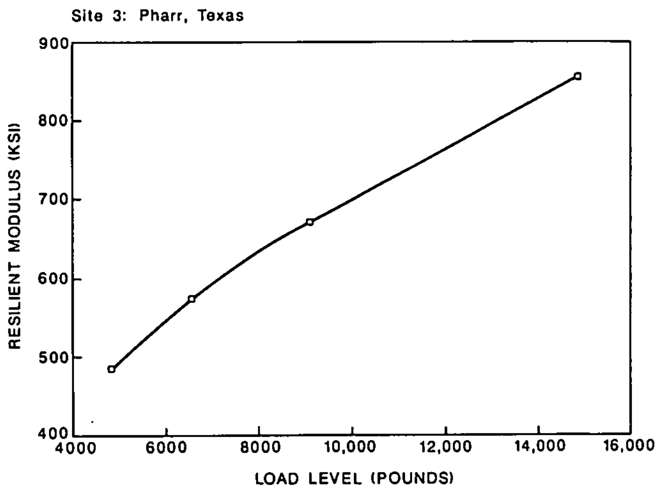


Figure 33. Typical response of backcalculated and laboratory asphaltic moduli to temperature and loading frequency.



Afternoon Readings at Location 1, December,1987

Figure 34. Stress sensitivity of asphaltic concrete.

the field associated with the backcalculated modulus was calculated at mid-depth in the base course layer. The stress state is defined by the confining pressure and the deviator stress. In order to calculate the confining pressure, the vertical overburden pressure (geostatic stress) was determined first from dry unit weights and moisture contents obtained in the field using a nuclear density/moisture gauge. The confining pressure was subsequently calculated by multiplying the vertical overburden pressure by the Poisson's ratio assigned to the base course layer in computer program MODULUS. Next, the deviator stress was determined by using either computer programs BISAR, CHEVRON, or ELSYM-5 for computing the vertical stress at the mid-depth of the base course resulting from the load imparted by the NDT device. This vertical stress is taken to be the deviator stress. The same state of stress as calculated above is used to obtain the resilient modulus from the laboratory test data. A review of the results is given by Scullion et al. (*6*). A typical result of comparison between laboratory and field backcalculated moduli is shown in Table 4, which indicates that there is a reasonable agreement between laboratory and backcalculated moduli. However, the agreement, in general, was not as close as was found for the asphaltic concrete. The remainder of the comparisons are many and are found in Appendix A.

Subgrade

Similar to the base course, the field state of stress needs to be calculated when comparing laboratory determined and backcalculated moduli of the subgrade. The manner in which this is done is identical to the procedure discussed for the base course, earlier, except that the depth of interest is taken to be 12 in. (30 cm) into the subgrade. Mid-depth of the subgrade is undefined, because the moduli backcalculations were performed with the assumption that the subgrade extends to an infinite depth.

A review of the results is presented by Scullion (*6*). Typical results are given in Table 5, which indicates that for the same stress state, the laboratory moduli were typically lower than the backcalculated moduli by up to 50 percent. The discrepancy between backcalculated and laboratory results is considered to be a consequence of the increase of subgrade modulus with depth due to increasing confining pressure of the overburden, and the fact that the stress state at a 1 ft (30 cm) depth into the subgrade is not representative of the entire mass of the subgrade.

Closer agreement between backcalculated and laboratory moduli occurs if the subgrade is divided into more layers. Nonetheless, the backcalculated subgrade moduli should be considered as average moduli. The full set of comparisons of the laboratory and backcalculated moduli are in Appendix A.

Table 4. Comparison of backcalculated and laboratory moduli for base course at site 1; Pharr, Texas.

Date Deflection Data Obtained	Average Temperature (°F)	Water Suction (Bars)	Pavement Location	Time	Stress State σ_3 (psi)	Stress State σ_d (psi)	FWD Load (lb)	Laboratory Moduli (ksi)	Back-Calculated Moduli (ksi)
10/1/87	81	-0.117	7	9:13 AM	1.	3.4	5480	18.9	15.9
			7	9:13 AM	1.	4.2	7192	18.5	13.8
			7	9:13 AM	1.	5.6	9880	18.0	13.8
			7	9:13 AM	1.	9.0	16,336.	16.6	14.5

Table 5. Comparison of backcalculated and laboratory moduli for subgrade at site 1; Pharr, Texas.

Date Deflection Data Obtained	Average Temperature (°F)	Water Suction (Bars)	Pavement Location	Time	Stress State σ_3 (psi)	Stress State σ_d (psi)	FWD Load (lb)	Laboratory Moduli (ksi)	Back-Calculated Moduli (ksi)
10/1/87	88	-0.137	7	9:13 AM	4.5	1.4	5480	29.9	65
			7	9:13 AM	4.5	1.6	7192	32.4	58
			7	9:13 AM	4.5	1.8	9880	32.2	55.
			7	9:13 AM	4.5	2.2	16,336.	34.8	52.5

CHAPTER THREE

INTERPRETATION, APPRAISAL, AND APPLICATIONS

INTRODUCTION

The whole field of nondestructive testing of pavements has changed significantly within the last 5 years. With the rapid change has come a much more widespread use of nondestructive testing and a broader and better understanding of its uses and limitations. At one time, before the initiation of the project, it was expected that a direct correlation between NDT devices based on center deflections was possible, with empirical adjustments based on the pavement structure and climate. It is now known, partly as a result of the studies conducted in this project, that correlations between devices can only be made between NDT devices when comparing corrected layer moduli, as was discussed in Chapter Two and shown in Figures 26, 27, and 28.

The whole field has matured in its expectations of NDT and the results of backcalculations of moduli from surface deflection measurements. The questions are no longer whether the methods and equipment used are capable of producing layer moduli, but how accurate they are, what the sources of errors are, how these errors can be reduced, and how the backcalculated results can be used in the design of new or rehabilitated pavements.

This chapter reflects those maturing viewpoints. A sound appraisal of the results of this project is that they have assisted in this positive development, and have raised and partly answered some of these relevant questions. This chapter reviews the results of the project and analyzes the sources of errors in backcalculation methods, suggests methods of reducing them, presents an appraisal of the current level of accuracy in making corrections to standard conditions, discusses the applications of the expert system developed in this project to assist in backcalculation, reviews the operational guidelines to NDT testing at network and project levels, and suggests ways of applying the results to rehabilitation methods.

ANALYSIS OF ERRORS IN BACKCALCULATION METHODS

Analysis of Sources of Errors and Methods of Reducing Them

The backcalculated moduli inevitably contain some degree of error. The major sources of error include the discrepancies between the theoretical model and actual pavement behavior, the errors introduced by convergence schemes, the errors due to inaccurate or incorrect input parameters, and the random errors introduced by the measurements themselves. It is important to be able to estimate the possible size of these errors, even though these errors are often confounded and are difficult to separate.

The discrepancies between the theoretical model and actual pavement behavior are numerous. Pavement materials are generally heterogeneous, anisotropic, and granular. Some materials are highly stress dependent (nonlinear) and some may become plastic or viscoelastic under elevated loads and temperatures. All of these deviate from the assumptions made in linear elastic theory. The use of the finite element method or other more sophisticated modeling may improve the similarity between the analytical model and reality, particularly in simulating a material's nonlinear behavior. However, such an increase in accuracy of description usually comes with a greater number of unknown parameters and makes backcalculation more difficult. The finite element method usually demands much greater computing power, and still it is not entirely successful in dealing with granular materials.

The popularity of using linear elastic theory is based on the fact that only two material parameters (Young's modulus and Poisson's ratio) are needed to predict the pavement deflections. In backcalculation, the less important parameter, Poisson's ratios, is usually assumed and only the Young's modulus of each layer needs to be calculated in order to match the surface deflections. Because each layer is represented by only one unknown, the number of surface deflections needed in backcalculation is equal to the number of layers with unknown moduli. This reduces the number of variables to be solved for and allows a direct search technique to be employed in converging to the effective layer moduli values.

With the currently available layered elastic solutions, several things can still be done to improve the backcalculation process. These include reducing the errors caused by convergence schemes and making a better estimation of the input parameters, such as Poisson's ratio, effective layer thickness, and the depth to the bedrock, if present. The latter is a significant contributor to the size of errors and is difficult to determine rapidly because it varies with each site. Experience, engineering judgment, and accurate data must be relied on for every backcalculation problem.

The objective of backcalculation stands not in matching the surface deflections perfectly, but in obtaining a reasonably good assessment of the underlying structure. Such an assessment usually can be achieved if other pertinent information is used (e.g., layer thickness, subgrade depth, and material type). On the other hand, without a thorough knowledge of the pavement structure, a good match of the surface deflection is still possible, but the resulting layer moduli values may not be meaningful in pavement evaluation. It should be noted that the error of backcalculation methods here means the accuracy in estimating the in-situ layer moduli, not the error in matching the surface deflections.

Because current backcalculation methods rely solely on the measured pavement surface deflection under a given load, it is difficult to backcalculate moduli of a thin surface layer or material properties other than the moduli. Simultaneous measurement of the impulse loads and dynamic deflections generated by the falling weight deflectometer may provide more information, but this technique is still under development at this stage.

Results of Study of Backcalculation Accuracy

In Chapter Two, reference was made to a study of the accuracy of backcalculation methods currently in use. A total of 26 deflection basins was used, eight of which were generated analytically.

Thirteen agencies participated in the exercise. The details of this study are in Appendix G.

The results of the survey showed a large variation of backcalculated moduli among the agencies, although five agencies consistently achieved reasonable results that were close to one another. Most agencies employed layered elastic theory in their analysis. However, significantly different results were found when different techniques were used in searching for the set of moduli that best fit the measured deflection basin. Even two agencies employing the same layered linear elastic program produced significantly different moduli because of the different input parameters assumed.

Because no "correct" values of the layer moduli were known in the 18 field pavement sections, the answers provided by one of the five most consistent agencies were used as a basis of comparison. Figures G-1 through G-12 show these comparisons. The correct answers were known in the eight deflection basins which were calculated. Comparisons of the agencies' results with the correct answers for each layer are shown in Figures G-13 and G-22. From this latter exercise, it is clear not only that several agencies were able to produce solutions that were more "reasonable" than others, but also that these same agencies performed better in backcalculating theoretically generated deflection basins. Hence, it is reasonable to infer that these agencies have better expertise in backcalculation of moduli values than the others.

Appendix G gives graphic evidence of the value of an expert or an expert system in backcalculation.

Accuracy of Corrections to Standard Conditions

Assessments of the procedures for correcting moduli to standard conditions are presented here. For the purpose of this evaluation, the backcalculated moduli are corrected to the same temperature and frequency at which the laboratory tests were run. The temperature is 77°F (25°C) and the frequency is 5 Hz. The Dynatest FWD was used as the standard NDT device to which the results of other NDT devices were corrected for comparison. Thus, the standard confining pressure and strain level were chosen to be those that result from a 9,000 lb (40 kN) load applied to the pavement surface using the Dynatest FWD.

The correction procedures were applied to moduli backcalculated from deflection basins obtained using the Dynatest FWD, Road Rater 2000, and Dynaflect. The deflection measurements were obtained on two pavement sections located at the Texas Transportation Institute's (TTI's) pavement test facility at Texas A&M University. Layer thicknesses and material descriptions are provided in Table 6.

Asphaltic Concrete

Two procedures were used to evaluate the temperature and frequency corrections for asphaltic concrete incorporated in Eq. 3. The evaluation procedure for the frequency correction required the correction of backcalculated asphaltic concrete moduli to standard conditions. The moduli were backcalculated from deflection data obtained using the Dynatest FWD, Road Rater 2000, and Dynaflect. Evaluation of the temperature correction procedure required obtaining an asphaltic concrete core from TTI's pavement test facility and determining its moduli at different temperatures for a given frequency.

Table 6. Pavement layer descriptions and thicknesses for sections 11 and 19 of the TTI pavement test facility.

Section 11

Layer	Material	Thickness
Surface	Hot Mix Asphalt Concrete	2.5 cm (1 inch)
Base	Crushed Limestone	41 cm (16 inches)
Subbase	Sandy Gravel	91 cm (36 inches)
Subgrade	Plastic Clay	Semi-infinite

Section 19

Layer	Material	Thickness
Surface	Hot Mix Asphalt Concrete	12.5 cm (5 inch)
Base	Crushed Limestone & 2% Lime	41 cm (16 inches)
Subbase	Sandy Clay	81 cm (32 inches)
Subgrade	Plastic Clay	Semi-infinite

Evaluation of the temperature correction is presented first. Only one asphaltic concrete core was taken at the TTI pavement test facility in order to minimize the disturbance to the facility and preserve its layered homogeneity. Because the asphaltic concrete at the facility was a plant mix and used on all of the facility's sections, moduli determined from the core were considered representative of the entire facility.

The resilient modulus of the core was determined in accordance to the repeated-load indirect tensile test (ASTM D4123). The core was 4 in. (10 cm) in diameter by 5 in. (12.5 cm) long and sawed in half across its diameter to obtain two specimens. Modulus values determined at each selected temperature for the two specimens were averaged for the subsequent analyses. Results of the laboratory test using a 0.1-sec load pulse every 3 sec (equivalent to loading frequency of approximately 5 Hz) are provided in Table 7. The averaged modulus for a given temperature was "corrected" to the other tested temperatures in Table 8, using Eq. 3 for comparison to the laboratory results.

The ratios of $E_{\text{corrected}}$ to $E_{\text{laboratory}}$ presented in Table 8 indicate that correcting a modulus measured at a low temperature to a higher temperature, e.g., 33°F (0.56°C) to 108°F (42°C), is less reliable than vice-versa. However, similar $E_{\text{corrected}}$ to $E_{\text{laboratory}}$ ratios were obtained for correcting a modulus at 108°F (42°C) to 77°F (25°C), as well as for correcting a modulus at 33°F (0.56°C) to 77°F (25°C). These trends may not be applicable to asphaltic concrete mixes differing from the mix used at the TTI Pavement Facility.

Figure 35 shows a comparison made by the Asphalt Institute (*4*) of predicted and laboratory-determined asphaltic concrete moduli. The predicted moduli were determined from the equation referred to in Ref. 49 as the "Witczak Modified |E*| Equation", or WME. It was from this equation that the frequency and temperature correction formula, Eq. 3, was derived. A consequence of this is that the $E_{\text{corrected}}$ to $E_{\text{laboratory}}$ ratios given in Table 8 should not be expected to be any better than the relative errors given in Figure 35.

Approximately all of the data points in Figure 35 are encompassed within a relative error range of +100 percent to −40 percent. Referring to Table 8, except for correcting the modulus at 108°F (42°C) to 33°F (0.56°C), the $E_{\text{corrected}}$ to $E_{\text{laboratory}}$ ratios are approximately comparable to the +100 percent to −40 percent relative error range.

Evaluation of the frequency correction was performed by backcalculating asphaltic concrete moduli using the computer program MODULUS and correcting them to a frequency of 5 Hz at 77°F (25°C). The moduli were backcalculated from deflection data provided in Appendix G obtained from the Dynatest FWD, Road Rater 2000, and Dynaflect. Additional data pertinent to these NDT devices, along with the pavement temperatures, are given in Table 9. Moduli backcalculated under conditions existing at the time of testing are given in Table 10, and the corresponding corrected moduli for standard conditions are given in Table 11.

Tables 10 and 11 are quite similar. However, the corrected asphaltic concrete moduli in Table 11 differed significantly from the 3.94×10^6 kPa laboratory test results. This discrepancy may be attributed to the systematic and random errors associated not only with the NDT devices and backcalculation analysis but also with the laboratory resilient modulus testing equipment.

Table 7. Asphaltic concrete mix properties (TTI pavement test facility).

Diametral Resilient Modulus (M_R) Results for a Loading Frequency of 5 Hertz:

	M_R		
Temperature	Sample 1	Sample 2	Average M_R
0.56°C (33°F)	9.25x10^6kPa(1341ksi)	7.08x10^6kPa(1027ksi)	8.16x10^6kPa(1184ksi)
25.00°C (77°F)	4.21x10^6kPa (611ksi)	3.68x10^6kPa (533ksi)	3.94x10^6kPa (572ksi)
42.00°C(108°F)	1.29x10^6kPa (167ksi)	1.15x10^6kPa (167ksi)	1.22x10^6kPa (177ksi)

Mechanical Gradation:

Sieve Size	Percent Passing
3/8"	100%
No. 4	98%
No. 10	78%
No. 40	26%
No. 80	14%
No. 200	7%

Penetration at 77°F - 8 dmm

Percent Asphalt by Weight - 6%

Table 8. Comparison of laboratory and frequency-temperature correction formula, Eq. 2.

Laboratory E	t	P_{ac}	F_{200}	(Hertz)	T_o	Corrected E_o	$\frac{E_{\text{Corrected}}}{E_{\text{laboratory}}}$
1.22x$10^6$1{a (177ksi)	42.00°C (100°F)	6%	7%	5	25.00°C (77°F) 0.56°C (33°F)	6.79x10^6kPa (985 ksi) 38.30x10^6kPa (5555 ksi)	1.72 4.69
3.94x10^6kPa (572 ksi)	25.00°C (77°F)	6%	7%	5	42.00°C (108°F) 0.56°C (33°F)	0.71x10^6kPa (103 ksi) 22.25x10^6kPa (3227 ksi)	0.58 2.73
8.16x10^6kPa (1184 ksi)	0.56°C (33°F)	6%	7%	5	25.00°C (77°F) 42.00°C (108°F)	1.45x10^6kPa (210 ksi) 0.26x10^6kPa (38 ksi)	0.37 0.21

Note: f = Test frequency

f_o = Corrected frequency

The corrected asphaltic concrete moduli for section 19 associated with the Road Rater and Dynaflect differ from the corrected moduli associated with the Dynatest FWD by approximately 31 percent for the Road Rater and 22 percent for the Dynaflect. These are acceptable levels of error between corrected moduli (see Table 13). However, for section 11, no significant differences were observable. This suggests that the discrepancies are a result of the systematic and random errors associated with the NDT devices.

Base Course and Subgrade Soils

Standard Load Level Correction

The procedure discussed in Chapter Two of this report for correcting a modulus to a standard load level, i.e., Eq. 6, was evaluated. A review of Tables 10 and 11 indicates that only the crushed limestone base of section 11 exhibited noticeable stress sensitivity. For this reason, application of the correction to a standard load level was limited to this base course. Evaluation of the temperature and moisture corrections will be presented subsequently.

Equation 6 was used in correcting the base course moduli to a standard load with the initial tangent moduli, E_{ik} and E_{ij}, set equal to the following regression equations:

$$E_{ik} = K_1 \left[\sigma_1 + \sigma_2 + \sigma_3 \right]_k^{K_2} \tag{10}$$

$$E_{ij} = K_1 \left[\sigma_1 + \sigma_2 + \sigma_3 \right]_j^{K_2} \tag{11}$$

where all the variables are the same as described previously. An attempt was made to use the laboratory-derived K_2 values

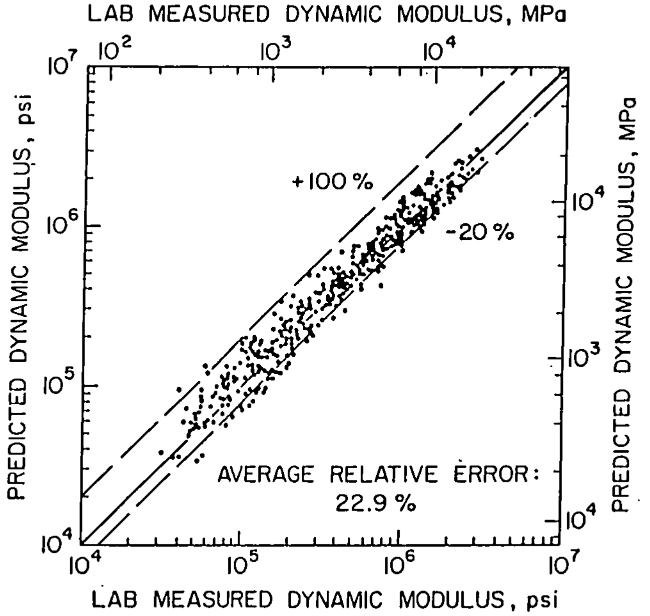


Figure 35. Comparison of predicted to measured dynamic modulus from Witczak modified $|E^*|$ equation.

Table 9. NDT device and pavement conditions.

Test No.	TTI Pavement Section	NDT Device	Time of Test	Pavement Temperature Surface	Pavement Temperature Average	NDT Frequency (Hertz)	Loading Plate Pressure	Loading Plate Radius
1	11	Dynatest 1^1	12:00pm	46°C(115°F)	43°C(110°F)	16.7	421kPa (61.1psi)	15.00cm(5.91in.)
2	11	Dynatest 2^1	12:00pm	46°C(115°F)	43°C(110°F)	16.7	586kPa (85.1psi)	15.00cm(5.91in.)
3	11	Dynatest 3^1	12:00pm	46°C(115°F)	43°C(110°F)	16.7	966kPa (140.1psi)	15.00cm(5.91in.)
4	11	Road Rater	11:00am	44°C(112°F)	42°C(108°F)	10.3	53.6kPa (7.8psi)	22.90cm(9.00in.)
5	11	Dynaflect	11:30am	42°C(108°F)	40°C(104°F)	8.0	857kPa (124.3psi)	4.10cm(1.60in.)
6	19	Dynatest 4^1	n/a	40°C(104°F)	37°C(99°F)	16.7	445kPa (64.6psi)	15.00cm(5.91in.)
7	19	Dynatest 5^1	n/a	40°C(104°F)	37°C(99°F)	16.7	630kPa (91.4psi)	15.00cm(5.91in.)
8	19	Dynatest 6^1	n/a	40°C(104°F)	37°C(99°F)	16.7	972kPa (141.0psi)	15.00cm(5.91in.)
9	19	Road Rater	n/a	39°C(103°F)	37°C(99°F)	25.3	53.1kPa (7.74psi)	22.90cm(9.00in.)
10	19	Dynaflect	n/a	39°C(103°F)	37°C(99°F)	8.0	857kPa (124.3psi)	4.10cm(1.60in.)

Note ^{1}Numbers 1 through 6 indicate different drop heights.

recommended in Table E-3, Appendix E, in this report for crushed limestone. Unsatisfactory results were obtained, as shown in Table 11, in the column covered by Note 3. Another means for obtaining K_2 directly from the field data was undertaken.

New K_2 values were determined by first calculating the initial tangent moduli from the backcalculated moduli (secant moduli) using step 1 and Eq. E-3 of Appendix E. BISAR (CHEVRON or ELSYM-5 could be used as well) was then used in conjunction with the backcalculated moduli to calculate the bulk stresses beneath the load at mid-depth in the base course. Next, as shown in Figure 36, a log-log plot of initial tangent moduli versus bulk stress was made. A linear regression of the plotted data on Figure 36 permitted the determination of K_2 and K_1, in which K_2 is the slope of the line and K_1 is the y-axis intercept.

The discrepancy between the backcalculation-derived K_2 value determined from Figure 36 (0.225) and the laboratory-derived K_2 values reported in Table E-3 (0.40 to 0.65) is due largely because the backcalculated modulus from a layered elastic method is an average modulus for the entire base course layer. This average modulus is not as sensitive to the calculated bulk stress beneath the load as is the same material when subject to the same bulk stress in a triaxial test apparatus. Had a finite element computer program been used, a K_2 value closer to those measured in the laboratory would be expected.

The bulk stresses given in Table 11 were calculated at the mid-depth of the crushed limestone base, directly beneath the loaded area of the NDT devices. The bulk stresses associated with the corrected moduli of the crushed limestone base are all reasonably similar as are the vertical strains (not shown) calculated at the same location as the bulk stresses. Because of this similarity of bulk stresses and vertical strains, the corrected crushed limestone base moduli are also quite similar for the various NDT devices (or loads) used.

Table 10. Backcalculated modulus values under test conditions.

Test No.	Asphaltic Concrete	Base Course	Subbase	Subgrade
1	1.92x10^{6}kPa (278.9ksi)	.38x10^{6}kPa (54.9ksi)	2.48x10^{5}kPa (36.0ksi)	1.92x10^{5}kPa (27.9ksi)
2	1.87x10^{6}kPa (271.1ksi)	.40x10^{6}kPa (58.2ksi)	2.23x10^{5}kPa (32.4ksi)	1.87x10^{5}kPa (27.1ksi)
3	2.02x10^{6}kPa (292.7ksi)	.46x10^{6}kPa (66.2ksi)	2.28x10^{5}kPa (33.0ksi)	1.45x10^{5}kPa (21.1ksi)
4	1.48x10^{6}kPa (214.3ksi)	.31x10^{6}kPa (45.4ksi)	2.68x10^{5}kPa (38.8ksi)	1.45x10^{5}kPa (21.1ksi)
5	2.42x10^{6}kPa (351.0ksi)	.24x10^{6}kPa (35.6ksi)	2.62x10^{5}kPa (38.0ksi)	1.77x10^{5}kPa (25.7ksi)
6	3.12x10^{6}kPa (453.1ksi)	3.62x10^{6}kPa (525.7ksi)	0.31x10^{5}kPa (4.5ksi)	3.12x10^{5}kPa (45.3ksi)
7	2.94x10^{6}kPa (426.8ksi)	3.69x10^{6}kPa (534.7ksi)	0.30x10^{5}kPa (4.4ksi)	3.02x10^{5}kPa (43.8ksi)
8	2.99x10^{6}kPa (434.0ksi)	3.27x10^{6}kPa (473.6ksi)	0.29x10^{5}kPa (4.2ksi)	2.88x10^{5}kPa (41.8ksi)
9	2.51x10^{6}kPa (363.5ksi)	4.06x10^{6}kPa (589.3ksi)	0.34x10^{5}kPa (5.0ksi)	3.41x10^{5}kPa (49.5ksi)
10	2.82x10^{6}kPa (409.4ksi)	2.82x10^{6}kPa (409.4ksi)	0.28x10^{5}kPa (4.1ksi)	2.82x10^{5}kPa (40.9ksi)

Table 11. Backcalculated modulus values corrected for frequency, temperature, and load level.

	Corrected Modulus Values[1] and Bulk Stresses			
Test No.	Asphaltic Concrete[2]	Base Course[3]	Base Course[4]	Bulk Stresses[5]
1	7.92x10^{6}kPa (1148ksi)	4.52x10^{5}kPa (65.5ksi)	3.99x10^{5}kPa (57.9ksi)	188.9kPa (27.4ksi)
2	7.69x10^{6}kPa (1116ksi)	3.93x10^{5}kPa (57.0ksi)	3.99x10^{5}kPa (57.8ksi)	184.5kPa (26.8ksi)
3	8.31x10^{6}kPa (1205ksi)	3.33x10^{5}kPa (48.3ksi)	4.15x10^{5}kPa (60.2ksi)	183.0kPa (26.5ksi)
4	7.94x10^{6}kPa (1152ksi)	9.02x10^{5}kPa (131.ksi)	4.36x10^{5}kPa (63.3ksi)	190.2kPa (27.6ksi)
5	9.10x10^{6}kPa (1320ksi)	8.10x10^{5}kPa (181.ksi)	3.57x10^{5}kPa (51.8ksi)	191.0kPa (27.7ksi)
6	6.70x10^{6}kPa (972ksi)	No Correction Required	No Correction Required	Not Required
7	6.31x10^{6}kPa (915ksi)	No Correction Required	No Correction Required	Not Required
8	6.42x10^{6}kPa (931ksi)	No Correction Required	No Correction Required	Not Required
9	4.47x10^{6}kPa (648ksi)	No Correction Required	No Correction Required	Not Required
10	7.90x10^{6}kPa (1146ksi)	No Correction Required	No Correction Required	Not Required

Note:

1. Correction to the subbase and subgrade moduli were not required.
2. Corrected to a frequency of 5 Hertz and temperature of 25°C (77°F).
3. Corrected to a loading pressure of 565kPa (82.0psi) applied over a loading plate of radius 15cm (5.91 inches) and using material properties of K_1 = 17,926kPa (2600psi) and K_2 = 0.65.
4. Same as 3 above except material properties of K_1 = 202.000kPa (29,353psi) and K_2 = 0.203 were used (see Figure 36)
5. Determined at mid-depth in crushed limestone base using moduli based on material properties given in 4 above.

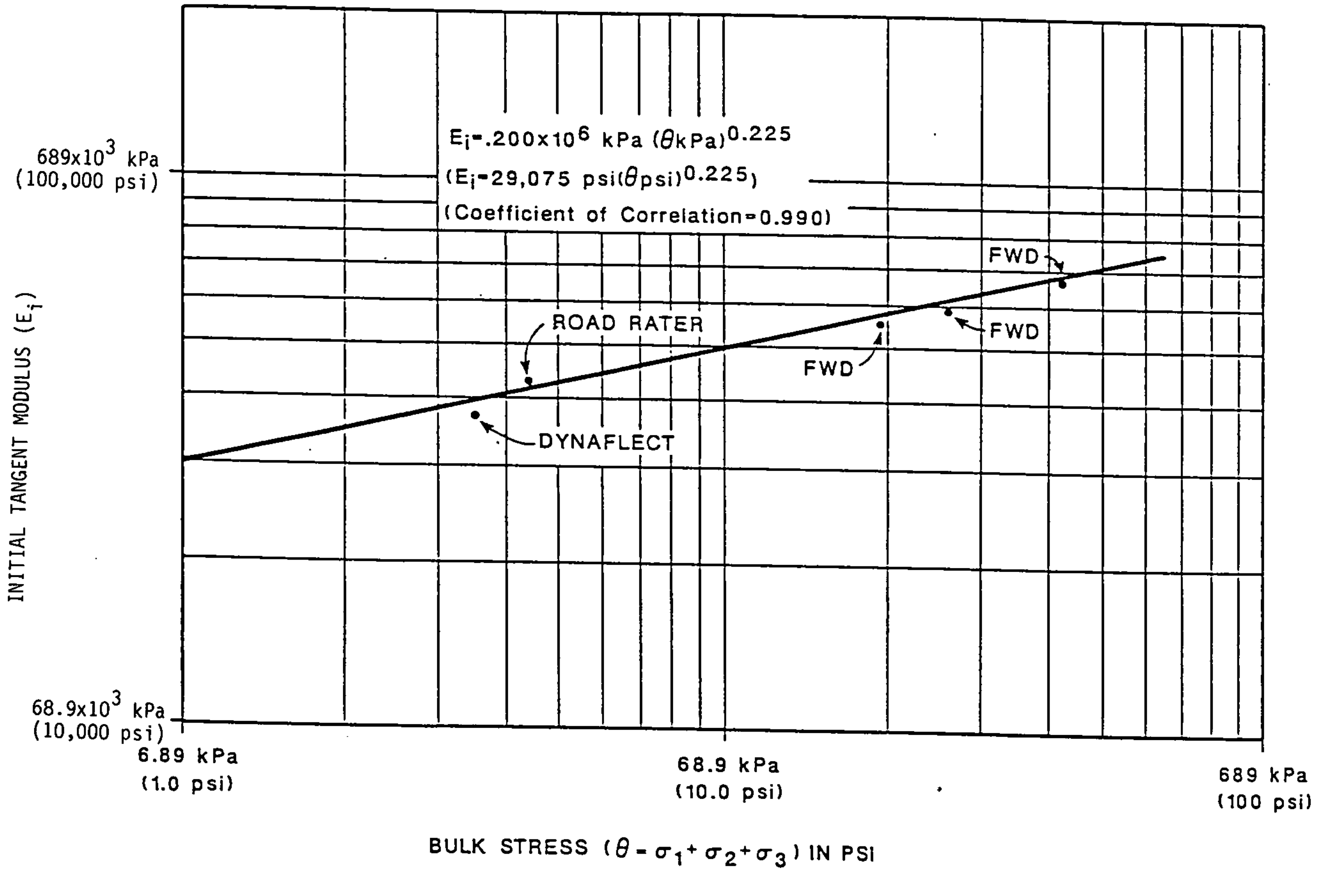


Figure 36. Resilient modulus backcalculated versus bulk stress for crushed limestone.

Moisture and Temperature Correction

An evaluation of Eq. 4 was performed using field deflection data obtained at the TTI pavement test facility and at sites 2, 6, 9, 12, and 16 (refer to Figure 29 and Appendix A for identification of the sites). The moduli were backcalculated from the computer program LOADRATE (*20*) and are referred to as "measured" moduli because they are calculated from the deflection basins. The computer program MODULUS could have been used just as well to backcalculate moduli, because the evaluation did not require the use of any particular computer program for backcalculation purposes.

Typical results obtained from hourly deflection data collected at section 11 of the TTI pavement test facility are described in the following. Hourly temperature measurements in the base course made over a 24-hour period in September 1987 varied from 85°F to 104°F. In order for the model to predict moduli at different temperatures, a reference modulus at a known temperature is required as one of the inputs. The base course mean temperature for the 24-hour period was 94°F and is used as the reference temperature. Because the system can be expected to come to equilibrium at the mean daily temperature, the reference modulus was chosen to correspond to this temperature. The reference modulus is the average of the modulus values backcalculated at each hour over the 24-hour period. Material parameters used in Eq. 4 are those for corresponding to limestone:

Elastic modulus = 10,000,000 psi
Poisson's ratio = 0.17
Linear thermal coefficient = 5×10^{-6}/°F
K_1 = that value assigned by LOADRATE
$K_2 = 0.33$

The results of the prediction are plotted in Figure 37. The predicted moduli and the backcalculated results have a similar trend of increasing as the temperature increases. The predicted moduli associated with the hourly temperatures are plotted in Figure 38 against the backcalculated moduli associated with the hourly temperatures. The points cluster along the line of equality, inferring that the predictions from Eq. 4 are in reasonable agreement with the measured moduli values.

In order to isolate moisture effects on base course moduli, deflection data with identical base course temperatures were analyzed. The results are presented in Table 12. Since the range of volumetric moisture content variations of granular materials is small, the initial volume fraction, θ_v, is assumed to be 0.13 for all of the calculations. At most of the sites shown in Table 12, the base course moduli for the different months, but with the same temperature, varied by less than 7 percent. Because of this, unfortunately, the effects on the modulus of the base course due to changes in suction were smaller than the normal coefficient of variation expected with the backcalculation method used. This

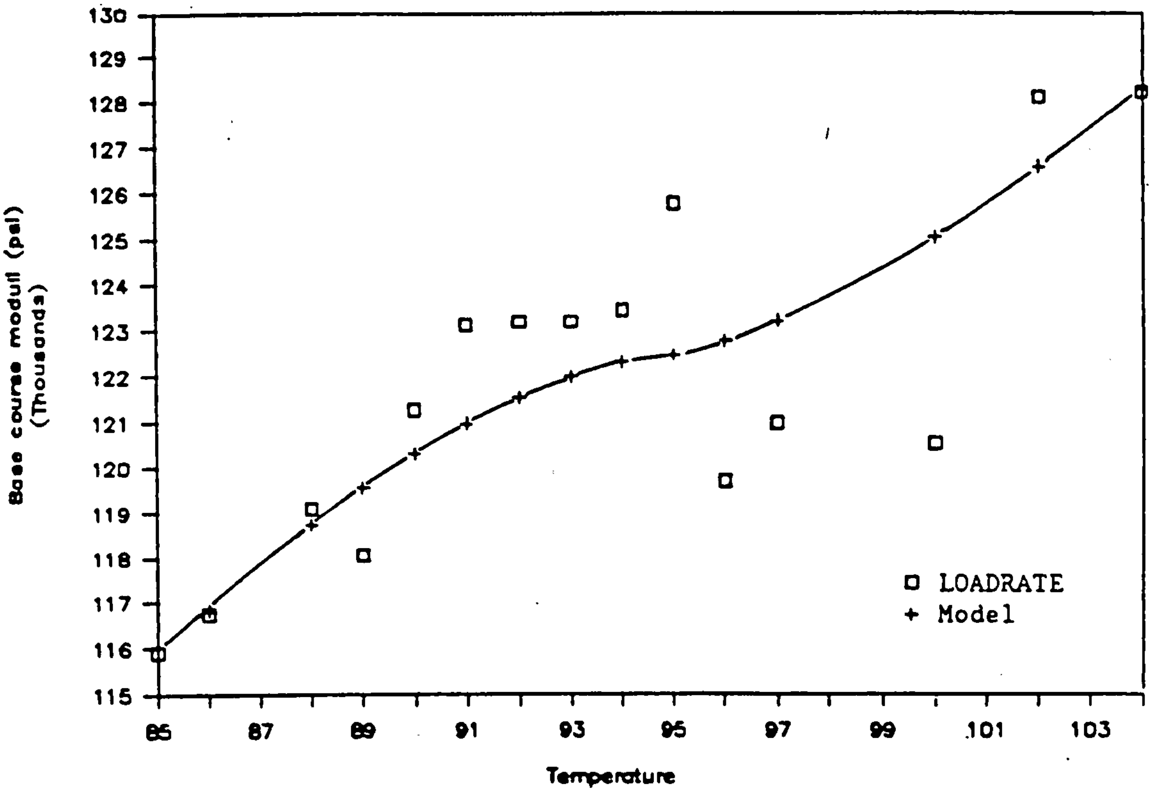


Figure 37. Comparison of the base course moduli from LOADRATE and the Model (Section 11 TTI Annex).

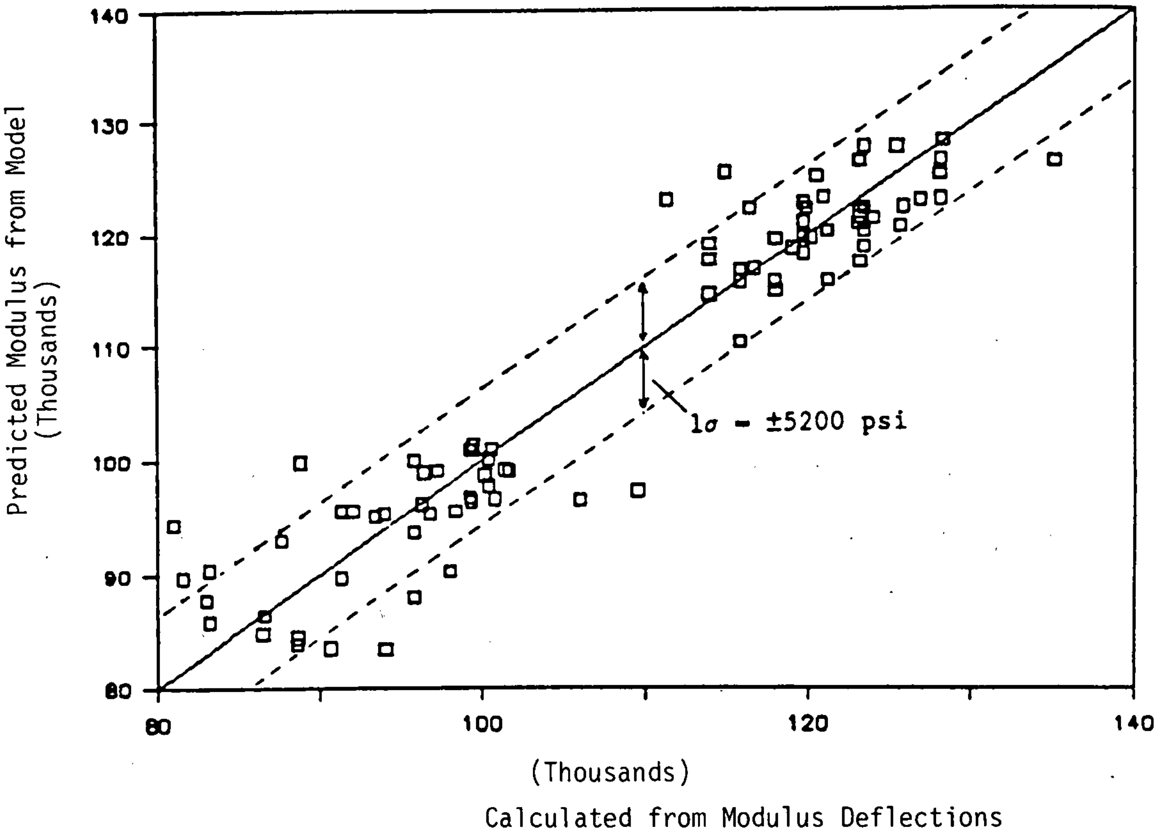


Figure 38. Predicted versus backcalculated (TTI Annex).

Table 12. Moisture effects on base course elastic moduli.

Site	E (psi)	K_1	θ (psi)	Δsuction (psi)	$\Delta\theta$ (psi)	Measured change of modulus	Predicted change of modulus
9	110,000	33,700	34.8	-59	+7.7	+7,000	+8,032
12	74,000	21,800	39.1	-15	+2.0	-2,900	+1,261
16	110,000	36,000	28.5	-2	+0.25	+5,000	+321
6	46,000	15,300	27.8	-10	+1.3	-3,000	+717
2	49,000	17,700	21.1	-1	+0.13	-3,400	+101

would be true regardless of the backcalculation method used.

However, when the fluctuations of the suction is large, as in the case of site 9, the effects of suction on moduli are apparent. In Figure 39, the month of October 1987 is used as reference, and all of the other moduli are predicted from the October modulus. The deflection readings were collected from different months in which there was a wide spread of base course temperatures. The base course modulus for each month was the mean value of the moduli backcalculated from ten deflection basins taken at the same location on the pavement. The solid line in Figure 39 denotes the predicted moduli without considering the suction effects. The dashed line, calculated by considering both temperature and suction variations, yields a closer prediction.

The same method is used to fit the base course moduli of site 16, where the suction readings were obtained by thermal moisture sensors. The results are plotted in Figure 40 which shows good agreement between the predicted and measured results.

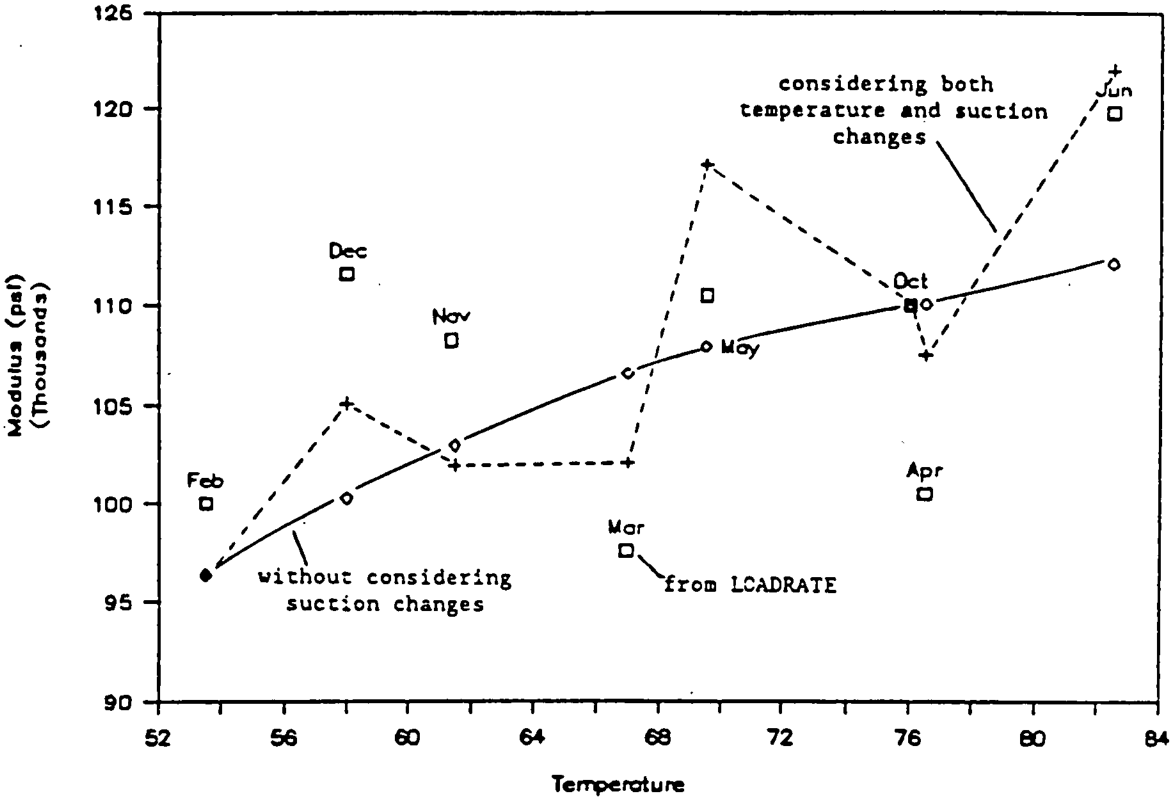


Figure 39. Comparison of the base course moduli from LOADRATE and the Model (site 9).

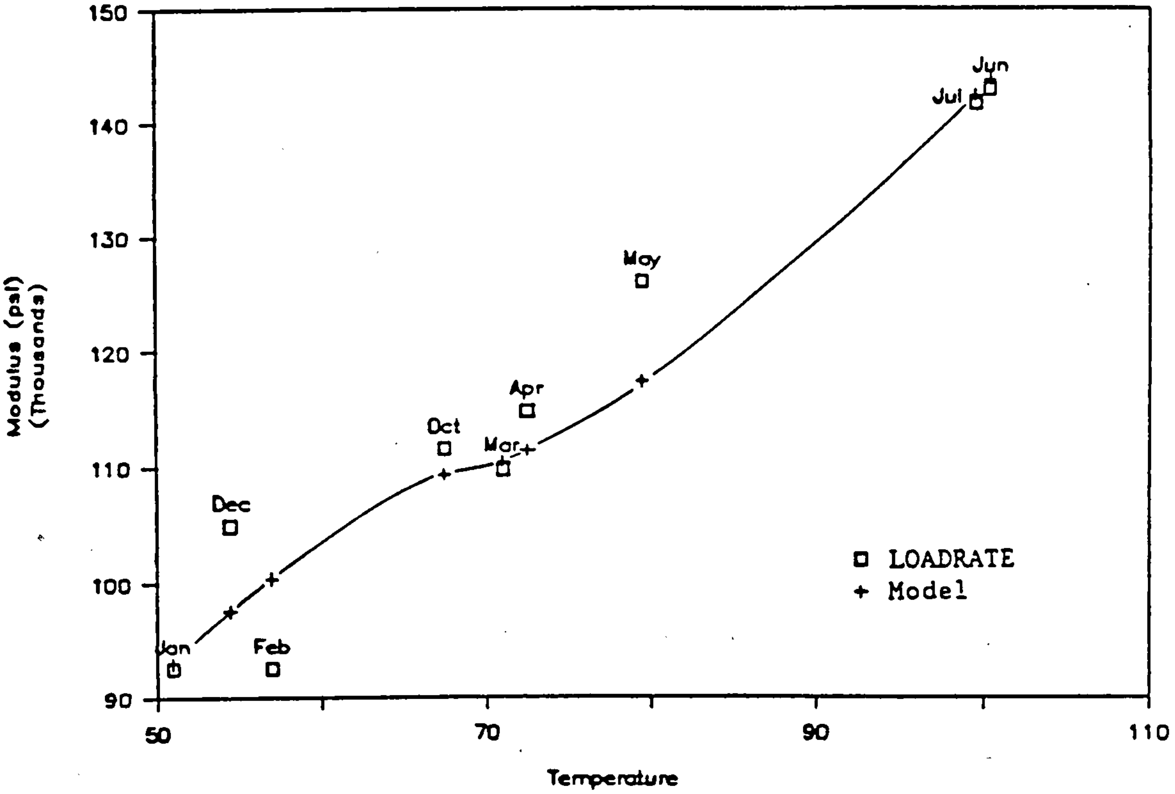


Figure 40. Comparison of the base course moduli from LOADRATE and the Model (site 16).

APPLICATION OF EXPERT SYSTEM TO DATA ANALYSIS

Expert System Overview

Expert systems have been characterized as problem-solving programs that solve problems generally considered as being difficult and requiring expertise. They have attracted considerable attention for their ability to solve complicated problems that can not be solved by any existing algorithms but require heuristic and judgmental knowledge (*23*). The expert systems area is a branch of artificial intelligence research which, in general, is concerned with how to simulate human intelligence by computer software. At present, expert systems can achieve close to human expert performance only when given a very specific task to solve, so that a narrow range of knowledge is required. The most widely used method of representing domain knowledge in an expert system is the use of production rules. In this method, knowledge is decomposed to many IF ⟨condition⟩ THEN ⟨action⟩ statements. For example, IF ⟨the pavement surface temperature is greater than 90 degrees F AND the asphalt layer is not aged⟩, THEN ⟨the asphalt concrete modulus should be less than 600,000 psi⟩.

The major components of an expert system include the knowledge base, context, inference mechanism, user interface, and sometimes, explanation facility. The knowledge base, which contains the problem solving information of a particular domain, is the most important part of an expert system. The context is where the specific information about the current problem is stored. The inference mechanism searches the knowledge base and the context to find a chain of reasoning that leads to the solution of the current problem. The user interface and explanation facility make the system easier to use.

The major characteristics that differentiate expert systems from conventional computer programs is the separation of the domain knowledge and the control knowledge. Nevertheless, some of the control knowledge, or problem solving strategy, is inseparable from the domain knowledge. It should be included in the knowledge base in order to make the expert system work efficiently. A flow diagram that corresponds to the line of reasoning of how a domain expert solves the problem is often necessary in organizing the knowledge base. A complete decision tree, however, is not required to build an expert system.

The most difficult task in building an expert system is acquiring domain knowledge from a human expert. In the engineering field, much of the knowledge is in procedural forms; still, the reason for using one analysis method over another and the difference between reality and analytical results requires a substantial amount of "engineering judgment". Experts are often unable or hesitate to reveal their rules-of-thumb or "private knowledge" on how to deal with difficult problems because of the informality of this kind of knowledge. But this private knowledge is what distinguishes an expert from the rest in dealing with difficult problems. It is suggested (*24*) that one effective way of acquiring the expert knowledge is through challenging the expert with difficult real domain problems and literally "watching" him solve these problems, recording every piece of information that is used by the expert. Reviewing and discussing with the expert all of the details in solving these problems may expose much of the expertise. This process is time consuming and requires pre-

Table 13. Statistics of NDT results within a design section.

	Normalized FWD Deflections (Mils)			MODULUS Calculated Layer Moduli (Ksi)			PASELS Estimated Layer Moduli (Ksi)		
	W1	W2	W7	E1	E2	E3	E1	E2	E3
Mean	20.99	12.16	1.45	345.7	43.3	16.2	317.1	33.1	16.0
Std.D.	4.90	2.58	0.27	184.2	30.4	3.3	95.1	11.8	2.7
COV(%)	23.3	21.3	18.3	53.3	70.2	20.4	30.0	35.6	17.1

cious time and cooperation from the expert. Yet, it is still the best known way of building a knowledge base. The backcalculation expert system is no exception.

Results of Analysis Using the Expert System

The PASELS expert system performs a basin-by-basin analysis of backcalculation results. It evaluates the rationality of the backcalculated layer modulus using knowledge stored in the knowledge base. If the backcalculated layer moduli become unreasonable, a rationally estimated value is suggested. Otherwise, the backcalculated moduli are accepted. The output of the PASELS system is dependent on each individual deflection basin and corresponding field condition, and may vary between adjacent basins. The result of using the PASELS expert system may be better illustrated by the following example problem.

Example Problem: A relatively uniform half-mile pavement segment on US77 near La Grange, Texas, was surveyed. The pavement consists of a multiple asphalt binding surface layer with a total thickness of about 4.5 in., a flexible base layer of about 5 in., and a clay subgrade roughly 30 ft deep. Twenty equally spaced FWD deflection test results were obtained. The deflections were normalized to correspond to a 9,000-lb load. The coefficient of variation (COV) of the deflections, as given in Table 13, is about 20 percent. The deflection data were then submitted for backcalculation. The COV of the backcalculated subgrade moduli is 20.4 percent, but the COVs of backcalculated surface and base layer moduli are 53.3 and 70.2 percent, respectively. This shows that the backcalculated base and surface layer moduli have much larger scatter than the subgrade moduli and the deflections. This is because MODULUS, as well as many other backcalculation procedures, determines the subgrade layer modulus first, and because of its greater depth from the surface and the fact that all of the sensors are sensitive to its properties, the subgrade moduli produced are more accurate. The other layer moduli are determined based on the calculated subgrade modulus. Any small error in the subgrade modulus may lead to large errors in the upper layer moduli because of their relatively smaller thicknesses, and the fact that measurement errors can be averaged over fewer sensors.

In this example problem, the COVs of the surface and base moduli are much larger than the COVs of the measured deflections and subgrade moduli, indicating that the surface and base layer moduli contain larger errors and are less reliable. The results of using the PASELS expert system are also given. The reduced COVs show that the expert system provides a more rational estimation of the layer moduli values.

APPRAISAL OF THE OPERATIONAL GUIDELINES

The operational guidelines developed in this project include the selection of equipment and analysis methods, data collection requirements, and the amount of testing for network level and project level analysis.

Even though FWD devices have been ranked highest by a utility analysis of all NDT equipment, it is not straightforward as to which FWD to choose among different manufacturers. Each FWD manufacturer has its unique specifications and different characteristics. It is not good practice to mix the data collected from different FWD devices without carefully verifying the compatibility. If possible, a single type of FWD device should be used within a highway network, so that the experience with that particular device can be accumulated and the data collected can be compared on the same basis.

The backcalculation program MODULUS, developed in this project, can backcalculate up to four unknown layer moduli (including subgrade moduli). It is not recommended to backcalculate more than four unknown moduli because of the possible nonuniqueness. Besides, none of the currently available design methods uses more than four layer moduli. The calculated surface deflections and matching errors reported by the MODULUS program are obtained by interpolation of a pregenerated data base, and thus the values are not exact. Nevertheless, the backcalculated moduli compare well with the results of BISDEF, an iterative program that takes much longer time to run, and can essentially reproduce input moduli when a forward-calculated deflection basin is given.

The importance of field data collection can not be overemphasized. No matter how good the analysis procedures are, the results will be useless or misleading if the data given are incorrect. NDT devices should be calibrated regularly, and a standardized procedure (e.g., ASTM Standard D 4694-87) should be followed for every test. The data that are not directly used by current backcalculation procedures, i.e., air and pavement temperatures, local topographic features, surface conditions, and drainage conditions, may provide vital information in preparing input and explaining the output of the backcalculations.

The number of deflection tests for network level analysis was determined based on the correlation of rankings. An important assumption is that the projects being ranked are of the same functional class. If the projects are of different functional classes, the ranking would not be based solely on measured surface deflections. However, the number of deflection tests required should remain the same.

LIMITATIONS OF THE CORRELATIONS DEVELOPED

Cautions must be taken when applying the developed deflection correlations between different NDT devices. It should be noted that any statistical correlation is based on a limited data set, and a generalization beyond the conditions to which the original data were subjected will prove to be erroneous. The correlations developed in this study were based on a restricted data set from the same location. Nevertheless, they serve to show that correlation of backcalculated layer moduli gives better results than the correlation of measured deflections. However, because of the differing loading mode and load level, the value of correlating different NDT devices appears to be limited. The difficulties and limitations in correlating NDT devices leads to the conclusion that one NDT device should be carefully selected and used.

APPLICATION TO REHABILITATION DESIGN METHODS

AASHTO Design Guide

The design process in the AASHTO "Guide for Design of Pavement Structures" (*2*) uses layer coefficients. One major factor in determining these coefficients is the layer resilient modulus. In recommending the estimation of layer resilient moduli with NDT methods, the AASHTO Guide recognizes the largely improved accuracy in estimating materials structural properties that NDT backcalculation methods can provide.

Elastic or resilient modulus is used by the AASHTO Guide for material characterization because it is a fundamental property of any paving or roadbed material. The AASHTO Guide requires that the seasonal resilient modulus values be determined to quantify the relative damage a pavement is subjected to during each season of the year and treat it as part of the overall design. An effective roadbed soil resilient modulus is then established, which is equivalent to the combined effect of all of the seasonal modulus values.

One of the procedures suggested by the AASHTO Guide for determining the seasonal variation of the roadbed soil modulus is to backcalculate the resilient modulus, for different seasons, using deflections measured on in-service pavements. It is necessary to separate the year into time intervals, such as a month or one-half month. The seasonal data are then translated into the effective roadbed soil resilient modulus by the following method. Relative damage, u_f, is obtained from:

$$u_f = 1.18 \times 10^8 M_R{}^{-2.32} \tag{12}$$

where M_R is the roadbed soil modulus in psi.

Summing the relative damage of every time interval and dividing by the number of time intervals, n, produce the mean relative damage, $\bar{u}_f$.

$$\bar{u}_f = \frac{1}{n} \sum_{f=1}^{n} \tag{13}$$

The effective roadbed soil resilient modulus corresponding to $\bar{u}_f$ can be obtained by substituting $\bar{u}_f$ into the left hand side of Eq. 12. The effective roadbed soil resilient modulus, thus determined, applies only to flexible pavements designed using the serviceability index criteria.

The AASHTO Guide also provides correlations to use layer resilient modulus values to estimate the structural layer coefficients (a_1, a_2, and a_3 values). For an asphaltic concrete surface course, Figure 41 may be used to estimate a_1 from E_{AC}, the layer resilient modulus, at a temperature of 68°F. Backcalculated layer moduli based on other temperatures must be adjusted back to this temperature to estimate the layer resilient modulus properly.

For a granular base layer, the following relationship may be used to estimate a_2 from the backcalculated layer modulus, corrected to a load level of 9,000 lb (40 kn):

$$a_2 = 0.249\,(\log_{10} E) - 0.977 \tag{14}$$

For a granular subbase layer, the following equation may be used to estimate a_3 from the backcalculated layer modulus, also corrected to a load level of 9,000 lb (40 kN):

$$a_3 = 0.227\,(\log_{10} E) - 0.839 \tag{15}$$

For cement-treated bases and bituminous-treated base layers, Figures 42 and 43 may be used, respectively, to estimate a_2 from their backcalculated and corrected modulus values.

FHWA Overlay Design Equations Method for Reflection Cracking

The Federal Highway Administration recently published a microcomputer-based design procedure for asphaltic concrete overlays of both flexible and jointed concrete pavement in which the type of distress addressed is reflection cracking (*26*). Several options are available in the design procedure for providing data on the existing pavement but, in the final analysis, what is needed for the design procedure for overlays of flexible pavements are the following: (1) thickness of old cracked asphaltic concrete layer; (2) elastic stiffness of the asphaltic concrete layer at the design service temperature; (3) average crack spacing; (4) shear and moment transfer efficiency across a crack; and (5) an effective coefficient of subgrade reaction of the entire pavement structure beneath the old cracked asphaltic concrete layer.

The microcomputer program has a backcalculation method included within it that determines items 2, 4, and 5 of the foregoing list from NDT deflection basins measured across a crack and in the center between cracks. The number 2 and 3 sensors in an FWD device are placed with a crack half way between them, and the deflections they record are termed w and w_u for the deflections on the loaded and unloaded sides of the crack, respectively. The maximum deflection when the deflection basin is measured in the central area between cracks is termed w_c. The bending transfer efficiency factor, f, is given by:

$$f = 2 - \frac{w_\ell + W_u}{2\,W_c} \tag{16}$$

Values of f range between 0 (poor moment transfer) and 1 (excellent moment transfer). The shear transfer efficiency factor, p, is given by:

$$p = \frac{W_\ell}{W_\ell + W_u} \tag{17}$$

Values of p range between 1 (poor shear transfer) and ½ (excellent shear transfer). The user must input the degree of load transfer across typical cracks in the old asphaltic concrete layer, described qualitatively as low, medium, and high levels of load transfer. These levels may be determined approximately from Table 14.

If the deflection is not measured at a temperature that is close enough to the design service temperature, it is better to use the MODULUS program to determine the layer moduli and correct them to the design temperature. The microcomputer program has another input option that permits the direct entry of layer moduli.

Through the use of the FHWA Overlay Design Equations Method, NDT measurements may be used in the design of asphaltic concrete overlays to withstand reflection cracking.

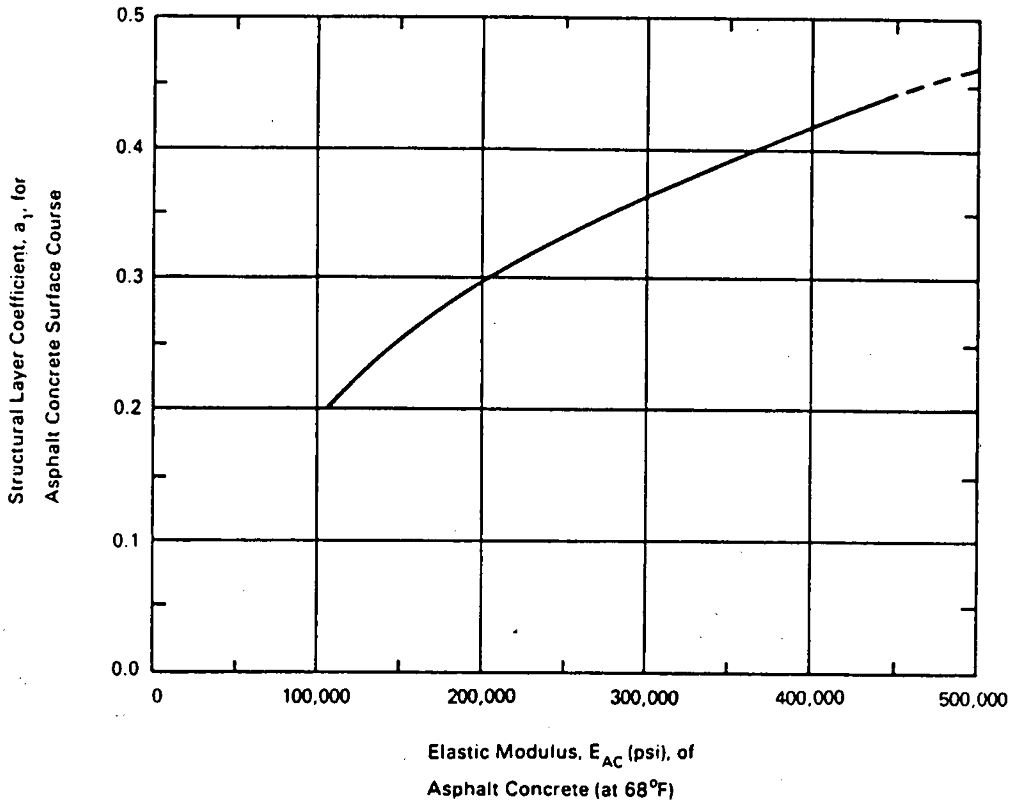
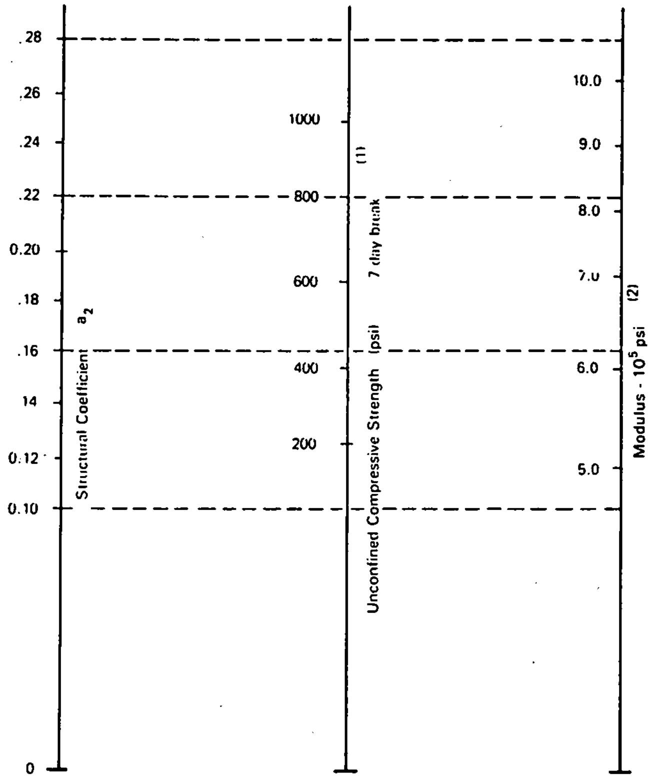
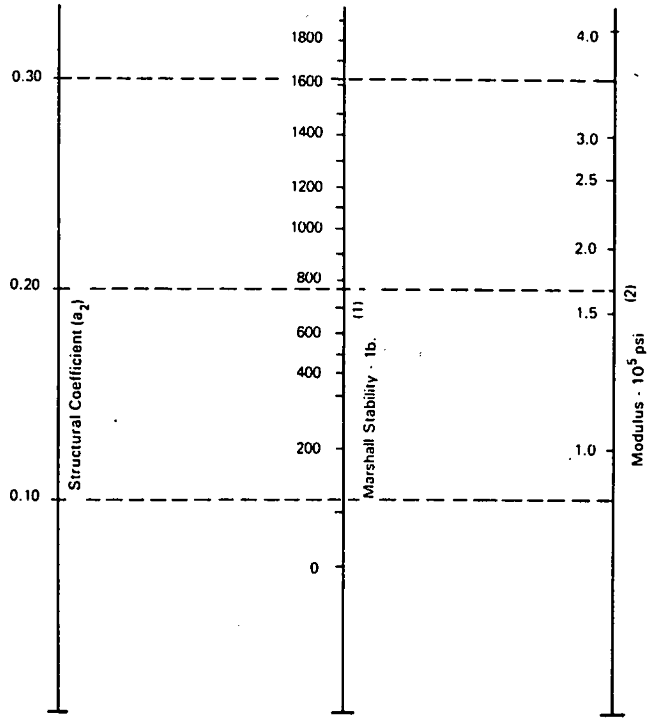


Figure 41. Chart for estimating structural layer coefficient of dense-graded asphalt concrete based on the elastic (resilient) modulus (2).



(1) Scale derived by averaging correlations from Illinois, Louisiana and Texas.
(2) Scale derived on NCHRP project (3).

Figure 42. Variation in a_2 for cement-treated bases with base-strength parameter (2).



(1) Scale derived by correlation obtained from Illinois.
(2) Scale derived on NCHRP project (3).

Figure 43. Variation in a_2 for bituminous-treated bases with base strength parameter (2).

Table 14. Shear and moment transfer efficiencies.

Degree of Load Transfer	Range of Shear Transfer Efficiency, p	Range of Moment Transfer Efficiency, f
Low	0.67 - 1.00	0.00 - 0.40
Medium	0.56 - 0.67	0.40 - 0.65
High	0.50 - 0.56	0.65 - 1.00

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The conclusions evolving from this project are in the areas of field data collection, analysis methods, expert systems, and accuracy of measurement.

Field Data Collection

Conclusions concerning field data collection are in the areas of nondestructive testing, temperature and moisture measurements, and needed improvements in equipment.

Nondestructive Testing

Nondestructive testing (NDT) is a fast and efficient means for collecting deflection data from which the material properties of pavement layers can be determined accurately, provided the following items are implemented.

A successful nondestructive testing program needs to know, with confidence, the layer thicknesses and the materials that comprise them. If this information is unavailable, test holes must be drilled to a depth of, preferably, 20 ft (6 m) unless bedrock is encountered at shallower depths. A more rapid means is required for determining layer thicknesses and the depth to bedrock.

Deflection data should be collected over intact portions of the pavement, i.e., portions that have minor to no cracking. The presence of cracks obscures the deflection data and, more importantly, the analysis methods considered in this study assume that the pavement materials are crack free.

When collecting data for the purpose of determining seasonal effects on pavement materials, the same location on the pavement must be used each time deflection data are collected to minimize the effects of construction and subgrade variability. Moreover, if the pavement is heavily traveled, care should be taken that traffic does not influence the deflections imposed by the NDT device.

Additional recommendations for enhancing the quality of deflection data collected are concerned with temperature and moisture (suction).

The presence of significant temperature and suction gradients can alter the response of a three-layer pavement section to that of a four, or more, layered pavement section. Temperature gradients can cause warping in the pavement, which will further distort deflection measurements. Temperature and suction gradients can be detected by installing instrumentation for measuring these physical quantities, or they can be predicted with acceptable accuracy. Otherwise, deflection data should be collected in the early morning hours when gradients are small or nonexistent.

Temperature Measurements

Temperatures can be measured accurately and dependably with the use of thermocouple wire. Several thermocouple wires can be attached to a wooden dowel, or a small diameter plastic tubing, at various locations corresponding to the depths of the layers and inserted in the pavement section. A digital thermometer is connected to the thermocouple wires whenever temperature readings are desired. Temperature gradients can easily and quickly be determined from the temperature readings obtained at the various depths.

Moisture (Suction) Measurements

Suction is a difficult quantity to measure, yet moisture content is even harder to measure. The most reliable piece of instrumentation available for measuring suction is the thermocouple psychrometer. These are electrical devices that are capable of measuring water potentials within the range of approximately −2 to −85 bars. Another electrical device that is available is the thermal moisture sensor. It is capable of measuring suctions within the range of approximately −0.5 to −3 bars. The thermal moisture sensor is new technology, which shows potential for use in pavements; however, at present, it is not recommended for routine monitoring.

Installation of the above devices requires drilling a test hole in the pavement section and installing the devices into the wall of the test hole in the base course and subgrade. This installation procedure limits the depth to which the devices can be placed.

A nonelectrical device for measuring suction less negative than −0.85 bars is the tensiometer. Unlike the electrical devices, this device must be maintained constantly. Moreover, a gage is attached to the tensiometer and needs to be concealed to prevent vandalism or other possible damage. Concealment of the tensiometer is difficult and expensive because the concealment structure would need to be constructed in the in-service pavement lane. Use of tensiometers is not recommended for routine monitoring.

Needed Improvements in Equipment

The more versatile of the NDT devices used during the course of this study was found to be those which apply an impulse loading, such as the Dynatest FWD. These devices can be altered with relative ease to suit particular situations or needs. Manufacturing loading plates with various diameters and stiffnesses for the purpose of imparting a uniform pressure to the pavement will enable NDT devices to more accurately model the boundary conditions assumed by layered linear elastic theory. Additionally, the NDT devices should be constructed in such a manner to accommodate arbitrary positioning of the deflection sensors. In general, enough flexibility should be built into NDT devices so that the they can conform reasonably well to the pavement section of interest and whatever theory is being used for the analysis of the deflection data.

With respect to the thermal moisture sensors, factual data must be provided regarding the accuracy of the calibration of the moisture sensors and the response of the sensors to changes in suction and temperature. Fredlund et al. (*9*) have evaluated the thermal moisture sensors, in part, and concluded that the moisture sensors have potential for geotechnical applications; experience with field measurements in this project has confirmed this finding.

New NDT devices using radar, sonar, or electrical conductivity may be needed to rapidly and accurately determine layer thickness and depth to bedrock. Use of impulse loading NDT devices with dynamic analysis methods may be capable of determining the depth to bedrock and may also provide additional materials data in each pavement layer.

Analysis Methods

Conclusions concerning analysis methods include the areas of data-base methods of analysis, error analysis, corrections to standard conditions, and correlations between NDT devices.

Data-Base Methods of Analysis

The computer program MODULUS layered linear elastic theory has proven to be the most efficient means for backcalculating moduli from deflection data. Approximately 15 min to an hour is required to generate the data base, depending on the complexity of the pavement section and the type of personal computer being used. The data base is generated automatically by MODULUS from input provided by the user consisting in part of layer thicknesses, probable ranges of moduli for each layer, and Poisson's ratios for the layers. Once the data base is established, MODULUS requires approximately 1 min to 2 min to backcalculate moduli through pattern search and Lagrangian interpolation techniques (*41*). Most importantly, MODULUS can backcalculate moduli for pavements having intermediate hard or soft layers. However, backcalculation of reasonable moduli for asphaltic concrete layers less than 3 in. (7.5 cm) thick is generally more difficult, requiring the use of the expert system developed in this project.

Error Analysis

In order to achieve reliable backcalculated moduli, the error between the calculated and measured deflections should be less than, or equal to, the manufacturer's specification for the deflection sensors, e.g., for the Dynatest this is ± 2 percent per sensor. If this tolerance can not be achieved, an attempt should be made to identify both the systematic and random errors and evaluate the possibility of eliminating them. Examples of these two categories of error were given in Chapter Two, and methods of reducing them were given in Chapter Three.

Correction to Standard Conditions

The need for corrections is brought about by the requirement to reduce systematic errors. The corrections themselves may have some level of error. The temperature and frequency corrections for asphaltic concrete were shown to have errors of the same size as the errors associated with the WME equation from which Eq. 3, the temperature and frequency correction equation for asphaltic concrete, was derived.

The correction procedure to adjust moduli at one load level to the standard load level should be undertaken after the asphaltic concrete modulus is corrected to standard temperature and loading frequency. The corrected value of the asphaltic concrete should be used in all subsequent calculations.

If the material properties a, b, m, in Table E-1, and K_1 through K_6 presented in Table E-3, are not considered representative of the actual material, or if it is essential to know precisely what these properties are for the material, cores should be taken and triaxial stress-strain tests made to determine the material properties. The correction procedure for load level can then be used with these experimentally determined properties. As an alternative, NDT devices capable of applying several load levels may be used to obtain material properties K_1 through K_6. Applying the load level corrections when the load is near the design load level, the material properties a, b, and m do not produce as significant a correction as the K_1 through K_6 values. For example, as shown in Table 15, the strain correction term is typically close to unity whereas the confining stress correction term is not. The only case in which the a, b, and m values result in large corrections is when a very light load needs to be corrected to a standard axle load level.

The effects of temperature and moisture on unbound materials were shown to obey the thermal and suction model, Eq. 4, reasonably well. The variations of base course moduli resulting from temperature and suction changes predicted by Eq. 4 agree well with the backcalculated moduli.

Correlations Between NDT Devices

The only reliable way to correlate the results of NDT measurements with different devices is to correct layer moduli to a common standard condition of load level, temperature, loading frequency, and moisture and find a correlation between the resulting layer moduli. The results of such correlations are excellent, as demonstrated in Chapter Three.

Use of Expert Systems in Data Analysis

It has been demonstrated that by using expert systems to automate the analysis of NDT data, it is possible to reduce the time required to process a large NDT data set and increase the accuracy of the results. Instead of spending a tremendous amount of their time in doing tedious basin-by-basin analysis, pavement engineers can rely on computers to do most of the work while being called upon only occasionally to make important decisions. Using an expert system in NDT data analysis also enables the less experienced analyst to obtain the same solutions as obtained by expert analyst, while understanding the rationality behind the solutions.

Accuracy of Measuring Asphaltic Concrete Moduli

The backcalculated asphaltic concrete moduli were shown to be in good agreement with the laboratory-determined moduli, provided that the error between the calculated and measured deflections did not exceed the accuracy of the deflection sensors. These criteria have only been applied to layered linear elastic analysis. Different criteria may have to be applied to analyses made with finite element computations.

In layered linear elastic theory, the most difficult layer for which to backcalculate a reasonable modulus is the uppermost layer. The better the match between calculated and measured deflections, the more reliable will be the backcalculated moduli. Any systematic and random errors that contribute to unacceptable discrepancies between calculated and measured deflections should be minimized if not eliminated. The prerequisites for backcalculating reasonable asphaltic concrete moduli include: accurate layer thicknesses, nearly isothermal conditions within each pavement layer, knowledge of the distribution of suction in the unbound layers, and the surface temperature. If these are taken into account and expert analysis of the deflection data is applied, a coefficient of variation of around 30 percent can be achieved consistently. At present, it is unreasonable to expect less variability from the results of a deflection survey. The accuracy of backcalculating the modulus of asphaltic concrete for a specific basin, assuming that random errors are reduced by repetition of the load and systematic errors are reduced by use of an expert system, is judged to be in the order of 10 to 20 percent.

SUGGESTED RESEARCH

Suggested research includes the areas of field data collection, analysis methods, and expert systems.

Field Data Collection

Suggested research in field data collection includes the areas of layer material properties, additional data needs, and equipment.

Table 15. Stress and strain correction values.

NDT Device	Corrected Crushed Limestone Modulus - E_2[1]	Stress Correction[2]	Strain Correction[3]
Dynatest	3.99×10^5 kPa (57.9 ksi)	1.0606	0.9951
Dynatest	3.99×10^5 kPa (57.8 ksi)	0.9924	1.0007
Dynatest	4.15×10^5 kPa (60.2 ksi)	0.8990	1.0117
Road Rates	4.36×10^5 kPa (63.3 ksi)	1.4183	0.9825
Dynaflect	3.57×10^5 kPa (51.8 ksi)	1.4855	0.9800

[1] Refer to Table 6, Note 4.

[2] Stress Correction $= \left[\dfrac{(\sigma_1 + \sigma_2 + \sigma_3)_k}{(\sigma_1 + \sigma_2 + \sigma_3)_j} \right]^{K_2}$

[3] Strain Correction $= \dfrac{a + \dfrac{(1-a)}{\left[1 + \left[\dfrac{(1-a)\epsilon_k}{b} \right]^m \right]^{1/m}}}{a + \dfrac{(1-a)}{\left[1 + \left[\dfrac{(1-a)\epsilon_j}{b} \right]^m \right]^{1/m}}}$

where

$a = 0.0749$
$b = 0.0261$
$m = 0.915$

Additional Layer Material Properties Needed

Pavement materials are affected by temperature, loading level and frequency, confining pressure, and suction. Those important to asphaltic concrete and other bound materials include temperature, loading frequency, and confining pressure. Those significant to unbound materials include all four of the physical parameters above. Confining pressures are needed if it is desired to establish a multiple layer linear model using the backcalculated moduli.

Additional Data to be Collected and Equipment Required

In this study, the confining pressures in a particular layer were determined by multiplying the vertical geostatic stress by the Poisson's ratio assigned to that particular layer for use in the computer program MODULUS. The vertical geostatic stress is the unit weight of the material multiplied by the depth of interest. In order to obtain an accurate estimate of the confining pressure, an accurate estimate of the unit weight and Poisson's ratio of each layer is required.

To determine Poisson's ratio, the value assigned as input for MODULUS may be used. If the error between the calculated and measured deflections is within the accuracy of the deflection sensor, the Poisson's ratios used in calculating the deflections should be considered reliable. If not, the more likely sources of systematic error are in the stress sensitivity of the moduli. Only after exploring this source should alterations be made in the Poisson's ratio. In-situ unit weights can be found in the construction records of various pavement layers. Other means for determining unit weights include nuclear density gages and sample retrieval for subsequent laboratory testing.

Temperature measurements are straightforward when using thermocouple wires and no further research is needed in this area. The same is true of predicted temperatures. Suction measurements are difficult to make and the source of difficulty varies with the type of sensor.

Thermocouple psychrometers are basically incapable of measuring suctions at and near full saturation. Moreover, the psychrometers when used in the field have a problematical life expectancy. However, they provide quite accurate measurements of suction within their working range of 3.5 to 5.0 pF.

Thermal moisture sensors are essentially in the developmental stage in which problems with their operation are being evaluated. A standardized procedure for their installation and for calibrating their output is still in progress. Theoretically, these sensors have the capability to measure suction in materials very near full saturation to slightly dry.

Tensiometers are proven technology, but are useful in only a very limited range of suctions less than atmospheric pressure. They can only measure water potentials less negative than approximately −0.85 bars. Additionally, the mechanical gages attached to the tensiometers make it difficult to install them in the locations, where they are required, and to keep them secure from vandalism.

An effort should be made to develop a procedure to measure suction with relative ease. The procedure envisioned here would be one that permits easy installation and extraction of suction instrumentation. A suggested approach would be to insert thermocouple psychrometers in a perforated plastic tube for installation in a hole drilled through the pavement section. In this manner, any psychrometers that become inoperable can be easily accessed by pulling the tube and replacing the inoperable psychrometer.

Reliable methods of predicting suction are being developed and validated with field measurements. Completion of this development and its practical implementation will be very desirable and beneficial.

Analysis Methods

The layered linear elastic computer program MODULUS can consistently backcalculate moduli for all layers of pavements having asphaltic concrete layer thicknesses of approximately 3 in. (7.5 cm), or more. Backcalculated asphaltic concrete moduli of pavements having thinner asphaltic concrete thicknesses are erratic and require experience or an expert system to achieve consistent results. Analysis methods employing techniques other than layered linear elastic analysis should be tried as well.

Promising Analysis Methods

Although layered linear elastic analysis can be used effectively to backcalculate moduli for many pavement types as done in this study, the modulus values are essentially the only material properties that are extracted. More progress can be made by using a more physically realistic model of the pavement response that takes into account dynamic effects, i.e., inertia and damping.

Dynamic analysis uses the full pulse time data for the applied force and all of the displacement sensors. The extra information in the time pulses can be used to extract more data on pavement material properties such as complex modulus, remaining fatigue life (cracking), and permanent deformation (rutting) properties.

Improvements in finite element methods to better represent bottom and side boundaries as elastic and to use better constitutive equations for the pavement layers will permit further reduction of systematic errors.

Use of Microcomputers

The MODULUS computer program developed in this study uses a microcomputer. A savings in time and costs regarding data collection can be realized by utilizing MODULUS in the field to backcalculate moduli and thus determine the quality of the deflection data. This approach to validating the deflection data is also applicable to other analysis methods. However, other analysis methods are more complicated than the layered linear elastic method and presently require the use of mainframe computers that preclude the capability of field validation of deflection data. This condition is expected to change in the near future. Research will continue to be required to develop efficient computer programs for use with microcomputers.

Future Development of the Expert System

The PASELS expert system program developed for this project is a prototype that is capable of being expanded to include a wide variety of expert opinion. Review by various pavement experts using field data and supplemented with local experience is needed before a final production system suitable for local applications is complete. This is a typical step in the development of expert systems and one of the reasons that successful implementation of expert systems has been relatively rare.

Currently, the PASELS system does not have the ability to "learn" from its experience, as an human expert does. Rather, the rule-base needs to be updated by human experts as experience accumulates or when new knowledge emerges. The ability to learn is a crucial criterion for a system to be called intelligent. Development of automated learning in the expert systems field has shown that the capability to learn may be achieved, but the effort to construct such a system can be extensive with current technology. In view of the importance of NDT to pavement analysis, design, and management, such a future development of PASELS is recommended.

REFERENCES

1. GIBBONS, J. D., *Nonparamatric Methods for Quantitative Analysis.* Holt, Rinehart and Winston, N.Y. (1976) pp. 275–284.
2. AASHTO *Guide for Design of Pavement Structures.* Vol. 3, American Association of State Highway and Transportation Officials, Washington, D.C. (1986) pp. 67–103.

3. Lytton, R. L., Roberts, F. L., Stoffels, S., "Determination of Asphaltic Concrete Pavement Structural Properties By Nondestructive Testing." Phase I Report, NCHRP Project 10-27 (Apr. 1986).
4. The Asphalt Institute, "Research and Development of the Asphalt Institute's Thickness Design Manual (MS-1) Ninth Edition." *Research Report No. 82-2* (Aug. 1982).
5. McKeen, R. G., "Field Studies of Airport Pavements On Expansive Clay." 4th International Conference On Expansive Clays, Volume I, American Society of Civil Engineers (June 1980).
6. Scullion, T., Michalak, C. H., and Lytton, R. L., "Nondestructive Test Procedures for Analyzing the Structural Condition of Pavements." Texas State Department of Highways and Public Transportation, Project No. 2-18-87-1123 (Anticipated completion of report, January 1990).
7. Cole, D., Bentley, D., Durell, G., and Johnson, T., "Resilient Modulus of Freeze-Thaw Affected Granular Soils for Pavement Design and Evaluation, Part 1. Laboratory Tests on Soils from Winchendon, Massachusetts, Test Sections." U.S. Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, *CRREL Report 86-4* (July 1986).
8. Letto, A. R., "A Computer Program for Function Optimization Using Pattern Search and Gradient Summation Techniques." Master of Engineering Thesis in Industrial Engineering, Texas A&M University, College Station, Texas (1980).
9. Fredlund, D. G., Wong, D. K. H., Imre, E., and Putz, G., "Evaluation of AGWA-II Thermal Conductivity Sensors for Soil Suction Measurement." Transportation Research Board, 68th Annual Meeting (Jan. 1989).
10. The Asphalt Institute, "Asphalt Overlays for Highways and Street Rehabilitation." Number 17 (1983).
11. Southgate, H. F., "An Evaluation of Temperature Distribution Within Asphalt Pavements and its Relationship to Pavement Deflection." *Research Report No. HRR-1(3),* Part II, KYKPR-64-20, Kentucky Department of Highways, Lexington (Apr. 1968).
12. Scrivner, F. H. and Moore, W. M., "Evaluation of the Stiffness of Individual Layers in a Specially Designed Pavement Facility from Surface Deflections." *Texas Transportation Institute Report No. 32-8* (June 1966).
13. Chandra, D., Chua, K. M., and Lytton, R. L., "Effects of Temperature and Moisture on the Load Response of Granular Base Course Material in Thin Pavements." Transportation Research Board, 68th Annual Meeting (Jan. 1989).
14. Saxton, K. E., Rawls, W. J., Romberger, J. S., and Papendick, R. I., "Estimating Generalized Soil-Water Characteristics from Texture." *Soil Sci. Soc. Am. J.,* Vol. 50 (1986).
15. Cole, D., Bentley, D., Durell, G., and Johnson, T., "Resilient Modulus of Freeze-Thaw Affected Granular Soils for Pavement Design and Evaluation—Part 1. Laboratory Tests on Soils from Winchendon, Massachusetts, Test Sections." U.S. Army Corps of Engineers, *Cold Regions Research & Engineering Laboratory Report No. 86-4* (July 1986).
16. Majidzadeh, K. and Ilves, G., "Flexible Pavement Overlay Design Procedures." Volumes 1 and 2, *FHWA-RD-81-032* and *82-033,* Federal Highway Administration, Washington, D.C. (Aug. 1981).
17. Gay, D. and Lytton, R. L., "Evaluation of Vertical Moisture Barriers." Texas State Department of Highways and Public Transportation, Project Study No. 1-10-77-187 (Anticipated completion of report, January 1990).
18. Dempsey, B. J., Herlache, W. A., and Patel, A. J., "The Climatic-Materials-Structural Pavement Analysis Program." Federal Highway Administration (Apr. 1984).
19. Lytton, R. L., Pufahl, D., and Liang, H. S., "Integrated Model for Predicting Climatic and Drainage Effects on Pavements." Final Report, FHWA Contract DTFH61-87-C-00057 (1989).
20. Chua, K. M. and Lytton, R. L., "Load Rating of Light Pavement Structures." *Transportation Research Record 1043,* TRB, National Research Council, Washington, D.C. (Jan. 1984).
21. Ullidtz, P., *Pavement Analysis.* Elsevier, Amsterdam (1987).
22. CLIPS Reference Manual, Version 4.0. (1987), "Mission Planning and Analysis Division's Artificial Intelligence Section." National Aeronautics and Space Administration, Houston, Texas.
23. Hayes-Roth, F., Waterman, D. A., and Lenat, D. (eds.) *Building Expert System.* Addison-Wesley, Reading, Mass. (1983).
24. Maher, M. L. (ed.) *Expert Systems for Civil Engineers: Technology and Application.* ASCE, New York, N.Y. (1987).
25. Jayawickrama, P. W., Smith, R. E., Lytton, R. L., and Tirado, M. R., Development of Asphalt Concrete Overlay Design Equations." Vols. I, II, III, Final Report FHWA Contract DTFH61-84-C-00053, Washington, D.C. (1987).
26. Richard, R. M., and Abbott, B. J., "Versatile Elastic-Plastic Stress-Strain Formula." Technical Note, *J., Eng. Mechan. Div.,* ASCE, Vol. 101, No. EM4 (Aug. 1963).
27. Kondner, R. L., "Hyperbolic Stress-Strain Response: Cohesive Soils." *J., Soil Mechan. and Found. Div.,* ASCE, Vol. 89, No. SM1 (Jan. 1963) pp. 115–143.
28. Duncan, J. M. and Chang, C. Y., "Non-Linear Analysis of Stress and Strain in Soils." *J., Soil Mechan. and Found. Div.,* ASCE, Vol. 96, No. SM5 (Sept. 1970) pp. 1629–1653.
29. Seed, H. B., and Idriss, I. M., "Soil Moduli and Damping Factors for Dynamic Response Analysis. *Report No. EERC-70-10,* Earthquake Engineering Research Center, University of California, Berkeley (Dec. 1970).
30. Stokoe, K. H., II, and Lodde, P. F., "Dynamic Response of San Francisco Bay Mud." *Proc.,* Earthquake Engineering and Soil Dynamics Conference, ASCE, Vol. II (1978) pp. 940–959.
31. Uddin, W., Meyer, A. H., Hudson, W. R., and Stokoe, K. H., II, "A Structural Evaluation Methodology for Pavements Based on Dynamic Deflections." *Research Report 387-1,* Center for Transportation Research, University of Texas at Austin (July 1985).
32. Majidzadeh, K. and Ilves, G., "Flexible Pavement Overlay Design Procedures." Vol. 1 and 2, *FHWA-RD-81-032* and *82-033,* Federal Highway Administration, Washington, D.C. (Aug. 1981).
33. Transportation Facilities Group, "ILLI-PAVE User's Manual." Department of Civil Engineering, University of Illinois at Urbana-Champaign (May 1982).
34. Hicks, R. G., and Monismith, C. L., "Factors Influencing the Resilient Response of Granular Materials." *Highway Research Board Record 345* (1971).

35. Chou, Yu T., "Evaluation of Nonlinear Resilient Moduli of Unbound Granular Materials from Accelerated Traffic Test Data." *Report No. FAA-RD-76-65,* U.S. Army Engineer Waterways Experiment Station (1976).
36. Uzan, J., "Granular Material Characterization." *Transportation Research Board* (1985).
37. Weinberger, H. F., *A First Course in Partial Differential Equations.* John Wiley & Sons, Inc. (1965).
38. Aklonis, J. J., MacKnight, W. J., Shen, M., *Introduction to Polymer Viscoelasticity.* John Wiley & Sons, Inc. (1972).
39. Lytton, R. L., and Chou, Y. J., "Modulus Back Calculation Exercise." Informal report to TRB Committee A2B05, Strength and Deformation Characteristics (Jan. 1988).
40. Uzan, J., and Lytton, R. L., "General Procedure for Back Calculating Layer Moduli. Submitted to the ASTM Symposium on Back Calculation, June 1988, *ASTM Special Technical Publication 1026.*
41. Waterman, D. A., "A Guide to Expert Systems." Addison-Wesley, Reading, Mass. (1986).
42. Kostem, C. N., and Maher, M. L. (eds.), "Expert Systems in Civil Engineering." ASCE, New York (1987).
43. Ritchie, S. G., "Microcomputer Expert Systems in Transportation Engineering." *Proc.,* North American Conference on Microcomputers in Transportation, ASCE, Boston, Mass. (1987).
44. Hall, K. T., Darter, M. I., Carpenter, S. H., Connor, J. M., "Development of a Demonstration Prototype Expert System for Concrete Pavement Evaluation." Presented at the 66th Annual TRB Meeting, January 1987.
45. Abkowitz, M. D. (ed.), *J. Computing in Civ. Eng.* (Expert System), ASCE, New York (Oct. 1987).
46. Wiseman, G., Uzan, J., and Greenstein, J., "Airfield Pavement Evaluation and Strengthening Based on NDT and Aided by an Expert System." Vol. I, *Proc.,* Sixth International Conference Structural Design of Asphalt Pavements, Ann Arbor, Michigan (July 1987).
47. Witczak, M. W., "Design of Full Depth Asphalt Airfield Pavements." *Proc.* Vol. I, Third International Conference on the Structure Design of Asphalt Pavements, Ann Arbor, Michigan (1972).
48. Shook, J. F., Finn, F. N., Witczak, M. W., Monismith, C. L., "Development of the Asphalt Institute Thickness Design Manual (MS-1), Ninth Edition." *Research Report No. 81-2 (RR-81-2),* The Asphalt Institute, College Park, Maryland (Aug. 1982) pp. 16.
49. Smith, B. E., Witczak, M. W., "Equivalent Granular Base Moduli: Prediction." *J. Transp. Eng.,* ASCE, Vol. 107, TE6 (Nov. 1981).
50. Lytton, R. L., and Chou, Y. J., "Modulus Back Calculation Exercise." Informal Report to TRB Committee A2B05, Strength and Deformation Characteristics (Jan. 1988).
51. Uzan, J., and Lytton, R. L., "General Procedure for Back Calculating Layer Moduli." Submitted to the ASTM Symposium on Back Calculation, June 1988, *ASTM Special Technical Publication 1026.*
52. Maher, M. L. (ed.), "Expert Systems for Civil Engineers: Technology and Application." ASCE, New York (1987).
53. *CLIPS Reference Manual Version 4.0.* Mission Planning and Analysis Division's Artificial Intelligence Section, National Aeronautics and Space Administration (Mar. 1987).
54. Hayes-Roth, F., Waterman, D. A., and Lenat, D. (eds.), "Building Expert Systems." Addison-Wesley, Reading, Mass. (1983).
55. Waterman, D. A., "A Guide to Expert Systems." Addison-Wesley, Reading, Mass. (1986).
56. Kostem, C. N., and Maher, M. L. (eds.), "Expert Systems in Civil Engineering." ASCE, New York (1987).
57. Ritchie, S. G., "Microcomputer Expert Systems in Transportation Engineering." *Proc.,* North American Conference on Microcomputers in Transportation, ASCE, Boston, Mass. (1987).
58. Hall, K. T., Darter, M. I., Carpenter, S. H., Connor, J. M., "Development of a Demonstration Prototype Expert System for Concrete Pavement Evaluation." Presented at the 66th Annual TRB Meeting (Jan. 1987).
59. Abkowitz, M. D. (ed.), *J. Computing in Civ. Eng. (Expert System),* ASCE, New York (Oct. 1987).
60. Wiseman, G., Uzan, J., and Greenstein, J., "Airfield Pavement Evaluation and Strengthening Based on NDT and Aided By an Expert System." Vol. I, *Proc.,* Sixth International Conference Structural Design of Asphalt Pavements, Ann Arbor, Michigan (July 1987).
61. Smith, B. E., Witczak, M. W., "Equivalent Granular Base Moduli: Prediction." *J. Transp. Eng.,* ASCE, Vol. 197, TE6, (Nov. 1981).
62. Witczak, M. W., "Design of Full Depth Asphalt Airfield Pavements." *Proc.,* Vol. I, Third International Conference on the Structure Design of Asphalt Pavements, Ann Arbor, Michigan (1972).
63. Shook, J. F., Finn, F. N., Witczak, M. W., Monismith, C. L., "Development of the Asphalt Institute Thickness Design Manual (MS-1), Ninth Edition." *Research Report No. 81-2 (RR-81-2),* The Asphalt Institute, College Park, Maryland (Aug. 1982) pp. 16.
64. Ullidtz, P., *Pavement Analysis,* Elsevier, Amsterdam, The Netherlands (1987).
65. *AASHTO Guide for Design of Pavement Structures.* American Association of State Highway and Transportation Officials, Washington, D.C. (1986).
66. Transportation Facilities Group, "ILLI-PAVE User's Manual." Department of Civil Engineering, University of Illinois at Urbana-Champaign (May 1982).
67. Hicks, R. G., and Monismith, C. L., "Factors Influencing the Resilient Response of Granular Materials." *Highway Research Board Record 345* (1971).
68. Chou, Yu T., "Evaluation of Nonlinear Resilient Moduli of Unbound Granular Materials from Accelerated Traffic Test Data." *Report No. FAA-RD-76-65,* U.S. Army Engineer Waterways Experiment Station (1976).
69. Uzan, J., "Granular Material Characterization." Transportation Research Board (1985).
70. Cole, D., Bentley, D., Durell, G., and Johnson, T., "Resilient Modulus of Freeze-Thaw Affected Granular Soils for Pavement Design and Evaluation, Part 1. Laboratory Tests on Soils from Winchendon, Massachusetts, Test Sections." U.S. Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, *CRREL Report 86-4* (July 1986).
71. Weinberger, H. F., *A First Course in Partial Differential Equations,* John Wiley & Sons, Inc. (1965).
72. Aklonis, J. J., MacKnight, W. J., Shen, M., *Introduction to Polymer Viscoelasticity,* John Wiley & Sons, Inc. (1972).

APPENDIX A

FIELD DEFLECTION DATA BACKCALCULATED MODULI AND LABORATORY TEST DATA

(See Note below.)

APPENDIX B

BACKCALCULATION OF NONLINEAR MODULUS PARAMETERS

NOTE

Only Appendixes C, D, E, F, H, and K of the agency final report are published herein. Appendixes A, B, G, I, and J of the original agency document are not published in this report. They are available on a loan basis or for the cost of reproduction from the NCHRP, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

APPENDIX C

DETERMINATION OF AMOUNT OF TESTS FOR NETWORK LEVEL NDT TESTING

Network level testing uses NDT results in identifying potential project sites, in determining relative priorities among projects, or in detecting differences of pavement behavior caused by factors such as climatic conditions, traffic patterns, or material types. In network level testing, a much smaller number of tests within a pavement segment are performed compared with project level testing. The number of tests required depends on the purpose of the testing.

In network level analysis, NDT is often used simply to rank sections as stronger or weaker than other pavements of the same pavement type which helps to determine the priorities among project sections. The problem always faced in network NDT is one of productivity: how few readings may be taken on each section in order to effectively rank the sections.

The Spearman's rank correlation technique (1) is used in comparing the different rankings. Eight sections of the same type of pavement, each one mile long, were used and a large number of FWD readings were taken on each of the sections. The ranking of these sections based on the mean values of the center deflections was considered as the "actual" ranking. Rankings based on a reduced number of tests were then compared with the "actual" ranking by calculating the Spearman's rank correlation coefficient between the two rankings. In this way, the minimum number of tests is found which generates a ranking that is still highly correlated with the "actual" ranking. This amount of testing is considered suitable for each section within a network level deflection survey.

The following steps were taken in determining the amount of NDT tests needed in network level analysis:

1. Eight Farm-to-Market road sections in Texas were tested. Forty FWD readings were taken at 150 foot intervals. A total of 40 readings per section were taken.
2. The means and standard deviations of the center deflections (W_1), the surface curvature index (SCI = W_1-W_2), and the outermost deflections (W_7) were calculated for each section.
3. Step (2) is repeated, assuming 20 readings per section were taken instead of the original 40 by selecting every other sample. The same is done for 10, 7, 5, 4 and 2 readings per section.
4. The mean values obtained above are tabulated, and the sections are ranked from lowest to highest in order of the mean deflection values. Based on 40 readings, the section which has the smallest mean value should have a rank = 1 (strongest), the section which has the largest mean value should have a rank = 8 (weakest).
5. The ranking obtained in (4) by using 40 readings per section are considered as the correct rankings. They are used to compare the rankings based on 20, 10, ..., 2 readings per section by applying a rank correlation technique (the Spearman rank correlation coefficient Rs) as described below:

Denote the rankings obtained by using 40 readings as x_i (i = 1, ... n), and denote the rankings obtained by using smaller sample sizes, e.g. 10

samples, as y_i (i =1, ..., n).

Hypotheses

Ho: The two rankings are independent

H_1: There is a direct relationship between the two rankings

Test Statistics (coefficient of rank correlation)

$$R_s = 1 - \frac{6 \sum_{i=1}^{n} d_i^2}{n\,(n^2 - 1)}$$

where d_i = difference between ranks of corresponding x and y

n = number of pairs of value (x,y) in the data

Rs = +1 when the rank of X is the same as the rank of Y for every pair of observations (perfect direct relationship).

Rs = -1 when the rank of X is in exactly the reverse order of Y (perfect inverse relationship).

Decision rule:

Reject Ho at confidence level a, if the computed value of Rs is greater than the critical value corresponding to 1 - a. The critical values of Rs for sample size 8 are shown in Table C1.

Table C1. Critical Values of Rs for n = 8

a	.001	.005	.010	.025	.050	.100
Rs	.9286	.8571	.8095	.7143	.6190	.5000

Depending on the confidence level chosen, the number of tests needed to give a ranking that is highly correlated to the actual ranking, which is the ranking that would be obtained by doing as many tests as possible, can be decided. Table C2. shows the results of the rankings based on the center deflection (W_1).

Table C2. Rankings of Sections Based on FWD Center Deflections

Sample Size	Pavement Sections and Their Ranking								
	FM785	FM251	FM249	FM323	FM974	FM3058B	FM1362	FM3058A	Rs
40	2	4	3	1	6	5	8	7	1.000
20	2	3	4	1	6	5	8	7	.976
10	2	3	4	1	5	7	8	6	.905
7	3	4	2	1	7	5	8	6	.871
5	2	6	3	1	7	5	8	4	.833
4	5	8	1	2	6	3	7	4	.476
2	4	8	1	3	6	5	7	2	.357

In this study it was concluded that five deflection readings per section was the minimum for structural ranking purposes. No matter which deflection characteristic was chosen: maximum deflection (W_1), least deflection (W_7), or surface curvature index (W_1 - W_2), the Spearman rank correlation coefficient became unacceptable below five readings per section.

APPENDIX D

DETERMINATION OF TEST SPACING FOR PROJECT LEVEL NDT TESTING

In project level analysis, the results of structural evaluation are often used to determine the rehabilitation design (i.e., overlay thickness). The accuracy of the evaluation affects the reliability of the design. A much larger number of NDT tests are needed than in network level analysis to ensure that a reliable and economical design will be reached. The fact that paving materials (including subgrade soils) are typically of varying properties makes the evaluation and design of pavement structures difficult. A pavement project can be divided, based on its responses such as NDT deflections, into relatively "uniform" design units. Within each design unit, the design parameter is determined using the mean and standard deviation values or a selected percentile value (e.g., 85 percentile). The number of NDT tests required thus depends on the reliability needed and the variability of the pavement deflections. In project level analysis it is often necessary to separate the project length into relatively uniform analysis units. These are pavement sections which exhibit statistically homogeneous attributes (cross sections, subgrade support, construction histories, etc.) and performance. NDT results can be used to delineate unit boundaries when accurate historic data are not available. An analytical method for delineating pavement units from NDT results is the cumulative difference approach (2). The basic concept of this approach is shown in Figure D1. A computer program named DELINE was written based on the cumulative difference approach. The minimum number of tests in project

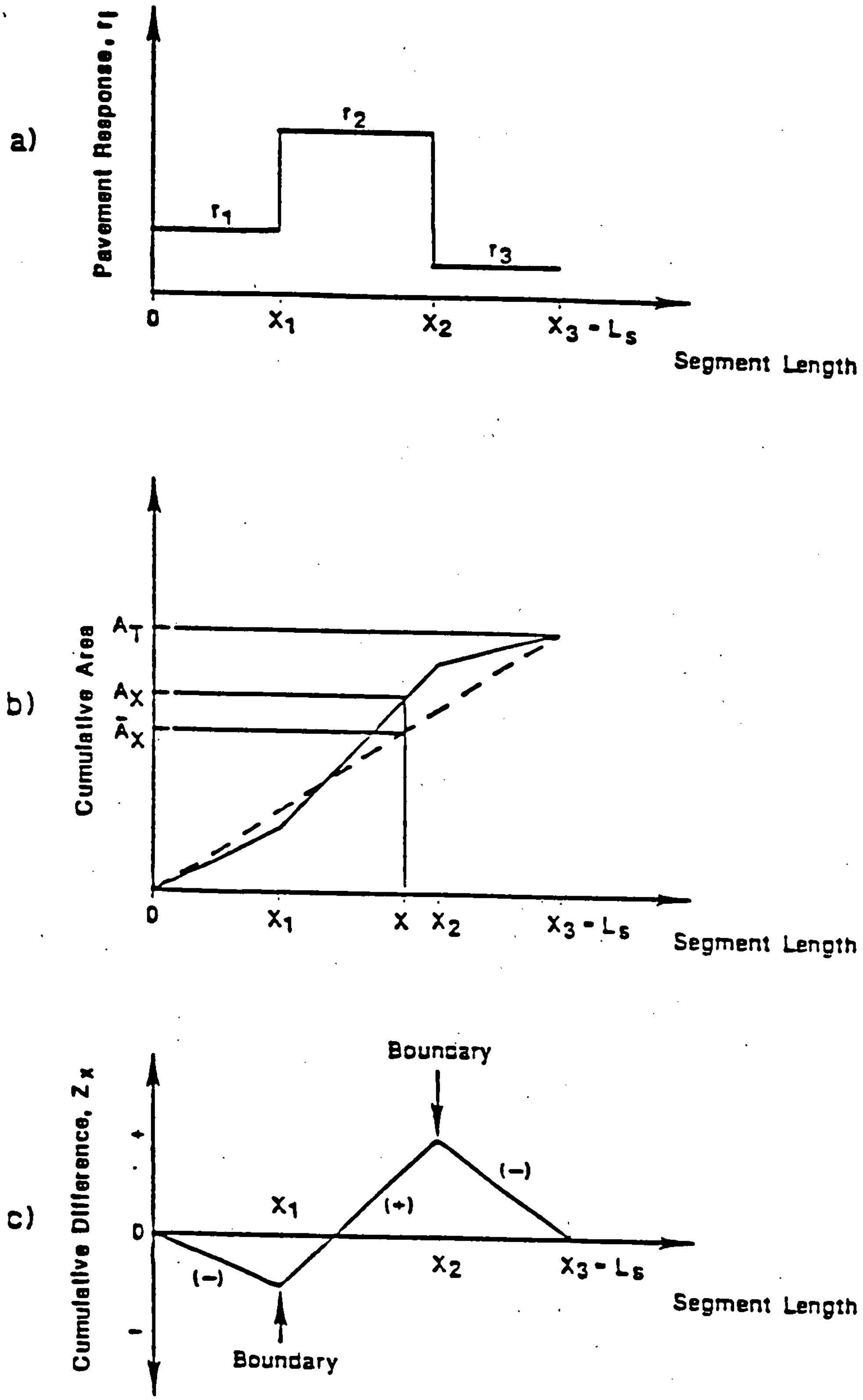
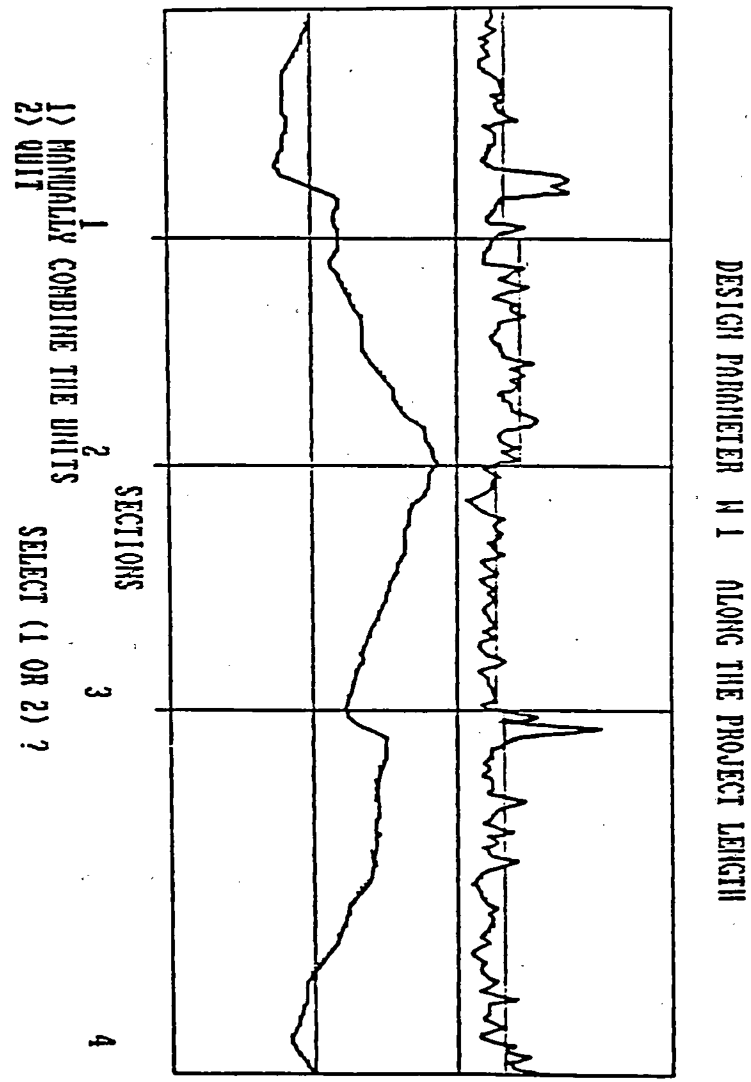


Figure D1. Basic Concept of the Cumulative Difference Approach to Unit Delineation level analysis was investigated by comparing the DELINE output of varying amount of tests. An sample output screen of DELINE is shown in Figure D2.

Several deflection basin parameters (e.g., W_1, W_2, SCI, and W_7) were input to the DELINE program for comparison. It was concluded from the six test sections that, except for W_7, all parameters generated essentially the same delineation results. Thus the maximum deflection, W_1, was used in determining the appropriate sample size.

The DELINE program also allows specification of the following options: first, the minimum length of an analysis unit according to practical design and construction considerations, and was assumed to be a quarter mile (1320 feet) in this study; second, the percentile of the design parameter within each analysis unit, and was assumed to be 80 percent; third, the difference of the design parameter value between two adjacent units which would be considered insignificant so that the two adjacent units can be combined into one unit, and was assumed to be 2.5 mils in this study.

Based on the above assumptions, results of the six test pavement sections from the aforementioned FWD deflection survey were input to the DELINE program. The number of units and unit boundaries based on the most intensive test intervals (50 feet) were then compared with those based on a reduced number of tests to find the minimum number of tests needed to identify appropriate analysis units. It was found that when test intervals were 100, 150, ..., 250 feet, the unit boundaries output by the DELINE program were about the same as the boundaries based on test intervals of 50 feet. When test intervals were greater than 300 feet,



```
DESIGN PARAMETER W 1  ALONG THE PROJECT LENGTH

        1            2            3            4
                  SECTIONS
1) MANUALLY COMBINE THE UNITS
2) QUIT
                   SELECT (1 OR 2) ?
```

Figure D2. Sample Screen Output of the DELINE Program however, the delineation results became considerably different. This was true for all six test sections. Hence it may be concluded that, for the delineating analysis units purpose, the FWD test intervals should be less than 300 feet.

When analysis units have been determined, the number of tests within each unit must be large enough to yield a rehabilitation strategy (such as an overlay design) that conforms to the required reliability. This puts a lower limit on the number of FWD tests within an analysis unit.

Depending on the size of the project, the available time and budget, and the purpose of the evaluation, the project level testing interval may vary from 25 ft to 300 ft. For the purpose of overlay design, testing should be performed in each wheel path every 100 to 300 ft. For more detailed analysis such as detecting localized base failures, testing should be performed every 25 to 50 ft.

In project level analysis, the amount of NDT testing has a direct influence on the accuracy of the estimation of the current pavement condition and the modulus of the surface layer, both of which in turn are the major inputs to overlay design. Thus, the amount of NDT testing affects how reliable the design will be. The determination of the amount of NDT testing is important, particularly when considering the relatively large variation of pavement deflections which reflect the large variation of subgrade and paving material properties.

APPENDIX E

CONSTITUTIVE EQUATIONS FOR PAVEMENT MATERIALS

INTRODUCTION

A simple method is needed for correcting backcalculated moduli derived from an NDT test to moduli under standard conditions imposed by a moving 9-kip (40kN) load at 70°F (21°C) traveling at highway speeds (8 Hertz or 0.0625 seconds load duration) and for the moisture condition. This appendix gives a detailed description of constitutive equations that may be used to correct moduli for load level and moisture in the base course and subgrade layers. There are two corrections that must be made to correct a modulus for load level: one for confining pressure and one for the strain level. Each of these will be treated separately and then they will be combined in the final section of this appendix.

The equation of the stress-strain curve for base, subbase, and subgrade materials is assumed to be of the form

$$\sigma = E_p \varepsilon + \frac{E_r \varepsilon}{\left[1 + \left|\frac{E_r \varepsilon}{\sigma_y}\right|^m\right]^{\frac{1}{m}}} \qquad \text{(E-1)}$$

where

σ, ϵ = the stress and strain values on the curve

E_p = the "plastic" or work-hardening modulus

E_r = $E_i - E_p$

E_i = the initial tangent modulus

σ_y = a maximum "plastic yield" stress m = an exponent

This equation was proposed by Richard and Abbott (27). A graph of the stress-strain curve described by this equation is shown in Figure E-1. If the exponent, m, is equal to 1.0, and the plastic modulus, E_p, is equal to 0.0, the equation becomes the familiar hyperbolic stress strain curve proposed by Kondner (28), used extensively by Duncan (29), and used in Chapter 4 of this report.

According to those references and others, the initial tangent modulus, E_i, varies with confining pressure, as will be described below. The modulus that is of interest in the analysis of pavements is a resilient modulus, that is the modulus describing the elastic deflection and rebound under a moving load. It is assumed here that the resilient modulus is a secant modulus of the curve shown in Figure E-1, and that it obeys the general hyperbolic stress-strain curve equation given above. The relation between the secant modulus, E, and the initial tangent modulus, E_i, in its simplest form is

$$\left[\frac{1-a}{\left(\frac{E}{E_i}-a\right)}\right]^m - \left[\frac{(1-a)\,\varepsilon}{b}\right]^m = 1 \qquad \text{(E-2)}$$

where

$$a = \frac{E_p}{E_i}\text{, and}$$

$$b = \frac{\sigma_y}{E_i}$$

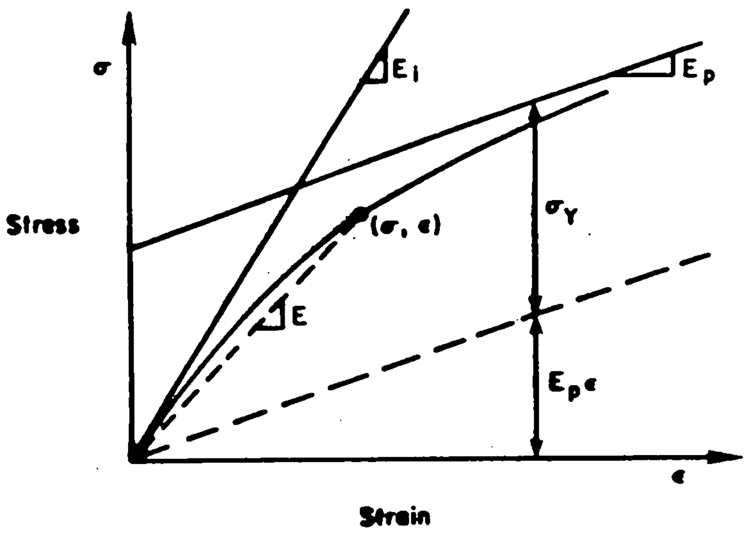


Figure E-1. General Hyperbolic Stress-strain Curve for Base, Subbase, and Subgrade Materials.

m, E_i = as defined above

The equation given above has four unknowns, a, b, m, and E_i which can be found by non-linear regression analysis of four or more points on a stress-strain curve.

Different load levels will produce different secant moduli on the same curve, assuming that the confining pressure does not change. If the confining pressure does change with load level, the ratio of the moduli between the two load levels must be adjusted for the change of the initial tangent modulus that has occurred. The corrections that must be made to adjust for changes in load level may be viewed as occurring in three steps:

Step 1. Find the ratio of the secant resilient modulus to the initial tangent modulus for each load level.

Step 2. Find the ratio of the two secant moduli, assuming the two initial tangent moduli are different.

Step 3. Find the ratio of the initial tangent moduli as they depend upon confining pressure.

Each of these steps are discussed in more detail below.

STEP 1. RATIO OF SECANT MODULUS TO INITIAL TANGENT MODULUS

For a load level, j, the ratio of the secant modulus, E_j, to the initial tangent modulus, E_{ij}, is

$$\frac{E_j}{E_{ij}} = a_j + \frac{1 - a_j}{\left[1 + \left[\frac{(1-a_j)}{b_j}\,\epsilon_j\right]^m\right]^{\frac{1}{m}}} \qquad \text{(E-3)}$$

where

$a_j = \dfrac{E_{pj}}{E_{ij}}$, the ratio of the "plastic" to the initial tangent modulus.

$b_j = \dfrac{\sigma_y}{E_{ij}}$, the ratio of the maximum plastic yield stress to the initial tangent modulus.

Similarily, for load level, k, the ratio of the secant modulus, E_k, to the initial tangent modulus, E_{ik}, is found using the same formula with the subscript k in place of j.

STEP 2. RATIO OF THE TWO SECANT MODULI

If E_k is the secant modulus at the standard load level and E_j is the secant modulus at some other load level, the desired modulus correction term is E_k/E_j. If it is assumed that the dimensionless constants a, b, and m do not vary with stress level, the desired correction term is given by

$$\frac{E_k}{E_j} = \frac{E_{ik}}{E_{ij}} \; \frac{a + \dfrac{(1-a)}{\left[1 + \left[\frac{(1-a)\,\epsilon_k}{b}\right]^m\right]^{\frac{1}{m}}}}{a + \dfrac{(1-a)}{\left[1 + \left[\frac{(1-a)\,\epsilon_j}{b}\right]^m\right]^{\frac{1}{m}}}} \qquad \text{(E-4)}$$

This expression is a function of the dimensionless constants a, b, and m, the two strain levels ϵ_k and ϵ_j, and the ratio between the two initial tangent moduli, which is related to the confining pressure ratio as explained in the next section. The strain, ϵ_k, is the strain under the standard load level and the strain, ϵ_j, is the strain under some other load level.

Typical values of the dimensionless constants a, b, and m are given in Table E-1. They were calculated from published repeated load stress-strain curve data from Seed and Idriss (30) and Stokoe (31).

The constant, a, is the ratio of the plastic modulus, E_p, to the initial tangent modulus, E_i, and represents the strain-hardening characteristic of the material. From Table E-1, it is apparent that both the fine-grained and granular soils exhibit a certain degree of strain-hardening.

The test data used to compute the constants given in Table E-1 come from resonant column tests in a torsional loading mode in which the modulus ratio is actually a ratio of shear moduli, G/G_{max}. Strictly speaking these modulus ratios have not been shown to be equal to the resilient modulus ratio, E/E_i, for the same soils. For the sake of future comparisons, the data points that were used to compute the dimensionless constants are given in Table E-2.

Although the test data were measured in a resonant column test, a similar analysis may be made of test data measured in a repeated load triaxial apparatus in which the confining pressure remains constant and the resilient moduli are determined at different levels of applied stress pulse.

The computer program that was used to make these calculations uses a non-linear regression technique and is listed at the end of this appendix. It may be used to analyze any set of repeated load data.

Table E-1. Dimensionless Constants for the Elasto-Plastic Hyperbolic Stress-Strain Curve.

Type of Soil	Dimensionless Constants a	b	m	Source of Stress-Strain Curve Data
Fine Grained	0.0529	0.0435	1.002	(30)
Granular	0.0749	0.0261	0.915	(31)

Table E-2. Dimensionless Stress-Strain Curve Data (32).

	Modulus Ratio, G/G_{max}	
Strain	Fine-Grained Soil	Granular Soil
0.0004	--	1.00
0.0010	1.00	0.98
0.0020	0.98	0.93
0.0030	0.95	0.89
0.0050	0.91	0.83
0.0070	--	0.78
0.0100	0.82	0.71
0.0200	0.72	0.56
0.0300	0.62	0.48
0.0500	0.51	0.39
0.0800	0.40	--
0.1000	0.35	0.28
0.2000	0.23	0.19
0.3000	--	0.15
0.7000	--	0.11
1.0000	--	0.10

STEP 3. CORRECTION FOR CONFINING PRESSURE

Depending upon the type of material, the correction term for confining pressure may be greater or less than 1. The initial tangent modulus, E_i, increases with confining pressure in granular materials and decreases with the deviator stress in fine-grained soils. In particular, with granular materials the equation for the initial tangent modulus, E_i, is either

$$E_i = K_1 (\theta)^{K_2} \tag{E-5}$$

where

$\theta = \sigma 1 + \sigma 2 + \sigma 3$

$\sigma_1, \sigma_2, \sigma_3$ = principal stresses

K_1, K_2 = material properties

or another form of E_i is

$$E_i = K_3 (\sigma 3)^{K_4} \tag{E-6}$$

$\sigma 3$ = the minimum principal stress

K_3, K_4 = material properties

For fine grained soils, the initial tangent modulus decreases with the deviator stress, σ_d, according to the following equation

$$E_i = K_5 (\sigma_d)^{K_6} \tag{E-7}$$

where

σ_d = the deviator stress, $(\sigma_1 - \sigma_3)$

σ_1, σ_3 = the maximum and minimum principal stresses

K_5, K_6 = material properties. The constant K_6 is usually negative.

Typical values of the constants K_1 through K_6 are given in Table E-3. These typical values are taken from Reference (33). The moduli produced by the constants in Table E-3 are in psi. Values of these constants that are intermediate between the maximum and minimum values shown in the table may be assumed to vary linearly between these limits on a log-log scale.

CORRECTION PROCEDURE

The procedure to correct a modulus to a standard load level requires an iterative process in which the confining pressure (θ, σ_3, or σ_d) and strain level are calculated both for the standard load and for the other load level. Because the secant moduli under the other load level are known from the analysis of the NDT data, it is necessary only to assume a modulus for each layer under the standard loading condition in order to get the calculation process started. Then the confining pressures and strains can be calculated for both loading conditions and corrected layer moduli under the standard load can be calculated, using the material properties tabulated earlier in this appendix.

If the new moduli are significantly different than those which were assumed, the calculation process is repeated using the new moduli until all calculated layer moduli are sufficiently close to those from

Table E-3. Typical Values of Base Course and Subgrade Constants K_1 Through K_6 (Moduli in psi).

Material		K_1	K_2	K_3	K_4	K_5	K_6
Crushed Stone	max			15,000	0.45		
	min			5,000	0.63		
Crushed Gravel	max	25,000	0.38				
	min	7,800	0.60				
Crushed Limestone	max	11,000	0.40				
	min	2,600	0.65				
Granitic Gneiss	max	34,000	0.19				
	min	1,500	0.73				
Basalt	max	8,900	0.47				
	min	4,700	0.65				
Sand	max			13,000	0.35		
	min			6,700	0.55		
Silty Sand	max	3,100	0.37				
	min	1,900	0.61				
Clayey Sand	max					25,000	-0.80
	min					--	--
Silty Clay	max					66,000	-0.38
	min					24,000	-0.11
Lean Clay	max					27,000	-0.50
	min					--	--
Highly Plastic Clay	max					25,000	-0.77
	min					--	--

(1 psi = 6.895 kPa)

which they were calculated. The most recently calculated moduli are the corrected values. Convergence of this process is fairly rapid, usually requiring no more than 3 to 5 iterations.

APPENDIX F

MODULUS USER'S MANUAL

The MODULUS program, a modulus backcalculation system described in this report has been developed by the Texas Transportation Institute on NCHRP Project 10-27. Any technical questions regarding this software should be directed to Chester Michalak or Miguel Paredes at the following address:

Pavement Systems Program
Texas Transportation Institute
Texas A&M University
College Station, Texas 77843
(409) 845-9912

The developed system is gneral in nature and can analyze data collected by most of the available NDT equipment (e.g. FWD or Dynaflect). The system has the following three major subsystems.

Susbsystem 1. Convert FWD Data to Input Data

This subbsystem reads the field diskette from a FWD (currently Dynatest version 9, 10, and 20 data format only) and creates a input file for the modulus backcalculation procedure. The field diskette file must have a .FWD extension and the created file is given the extension .OUT. For NDT data not in this format, a coding form (attached) is available which describes the format of the .OUT file. This subsystem can be skipped if the .OUT file is created independently.

Subsystem 2. Modulus Backcalculation

Reads the .OUT file, performs the backcalculation and creates a .DAT file, which contains the calculation E values.

Subsystem 3. Plot Deflection

Graphically displays the data stored in the .DAT file and performs subsectioning.

While running the backcalculation several options are available including fixing a depth to a rigid layer and setting the modulus of a layer to a fixed value. The system can be used for 2, 3 or 4 layer analysis.

1. INTRODUCTION

A. Getting Started

The TTI MODULUS Analysis System program is distributed in a 5¼" 360KB floppy disk. To make backup copies of this diskette, use the DISCOPY command from DOS to insure that all the files are copied to the backup diskette.

Check the disk directory to see if a TTIREAD.ME file exists. If it is there, you can list it either on the screen using the TYPE command, or on the printer via the PRINT command. This file contains the most current information and/or special instructions pertinent to the latest version of the software and it should supersede any information found in the User's Manual.

B. System Requirements

Minimum system requirements to run the program are:

- IBM AT or compatible microcomputer
- 640 KB or RAM
- DOS (version 3.00 or later) operating system
- Math coprocessor chip (80287, 80387, or similar)
- A hard disk with 1MB of available storage space
- A EGA or VGA graphics card with 256 kb of screen memory and a compatible RGB or monochrome monitor
- Printer

It is recommended that an advanced microcomputer, a 286 or even a 386 based machine, be used in order to minimize program execution time.

C. File Naming Conventions

The TTI MODULUS Analysis Systems program uses several types of files. The type of each of these files is identified by the three letter extension to the filename:

• .LBR:	Input/output screen display library.
• .BIS:	A file produced by the MODBAC program. It contains information later used by the CHEVRON program.
• .DA1:	These files contain the final results.

.DA2: The PRMODRES program uses these files to produce summary and detailed output tables which can be sent to a printer.

•TMP.DEF: This file contains input information provided by the user when selecting input option three. The information is later used by the MODBAC, CHEVRON, and SERMOD programs.

•BIS,RES: This file stores the normalized deflection bowls that are calculated when the user supplies all input information using input option three. The file is used by the same programs as TMP.DEF.

•TMP1.DEF: to TMP24.DEF These files contain default information for 24 to to fixed pavement designs. If any of the fixed TMP24.DEF designs is selected, the corresponding file is renamed to TMP.DEF and used as the original file.

•BIS1.RES to TMP24.RES Similar to the above. These files are renamed BIS.RES and then used as the original.

• .DAT: Files with this extension store deflection readings and corresponding backcalculated moduli for each available road section. This data is used by the EDLINIAT program. The DESIGN.DAT file contains the default names for the fixed analysis option of the modulus backcalculation subsystem. See the section on "Customizing Fixed Designs" for instructions on how the user can create its own fixed designs. The DEFAULT.DAT file stores default values for options two and three of the modulus backcalculation subsystem.

• .EXE: Identifies executable files.

• .FWD: The master data file as obtained from the Falling Weight Deflectometer.

• .OUT: These files are produced by the FWDREAD program. They contain deflection information extracted from the FWD files (.FWD). This file can also be created externally using the coding sheet attached to the end of this manual.

• .VAL: A special file containing Poisson Ratio values for each pavement layer. This particular file is only used for output purposed by the PRMODRES program.

• .BAT: Batch files used for installation of the system in a hard disk and for setting up and starting the program.

D. Installing the TTI MODULUS Analysis System Software

To install the TTI MODULUS Analysis System programs in the hard disk, insert the distribution diskette in one of the computer's floppy disk drives and then transfer to that drive. For instance, if the drive is A:, insert the diskette in the drive, and type:

```
A: <ENTER>
```

The distribution disk contains an installation program called INSTALL.BAT. When executed, this batch file creates a special directory in the computer's hard disk and copies all the necessary files to that directory. Before running INSTALL.BAT, you must decide what name you want for the directory. Suppose you want to install the program on partition C: of the hard disk and that you want the directory where the program files will reside to be called MODULUS. To run install with these parameters type:

```
INSTALL C:\MODULUS <ENTER>
```

INSTALL will create a directory called MODULUS in drive C: and then transfer all the files from the floppy disk to the new directory.

2. RUNNING THE PROGRAM

Starting the Program

To run the TTI MODULUS Analysis System programs, make the MODULUS subdirectory active by typing CD\MODULUS after the DOS prompt. If another drive is active, type the letter of the drive where the system has been installed and press <ENTER>; then type CD\MODULUS.

Once in the MODULUS directory, type MODULUS followed by <ENTER> to start the program. After a few seconds, the introductory screen will be displayed. Press any key to display the copyright information screen. Again, press any key and this time the main program should appear on the screen, see Figure F1.

Main Program Menu Options

The Main Program Menu screen allows the selection of any of the

four available programs. To execute any of the programs, use the up/down arrow keys to highlight the selection and press <ENTER>. All menus in this package work in the same way.

The following programs are available:

- Convert FWD to INPUT Data: This program reads in files that have been produced in the field (FWD files) while recording deflection information and converts them to a format that is compatible with the Modulus Backcalculation program. This is a custom-built program handling the FWD data files available with the Dynatest FWD.
- Run Modulus Backcalculation Program: This option allows the user to execute the Modulus Backcalculation (MODULUS) program. This program uses INPUT files (files with the .OUT extension) that have been converted from FWD files using option one above, or it can also process files that have been custom-made using a text editor or similar program.
- Plot Deflection and/or Moduli Values: Select this option to produce plots of deflection data or backcalculated moduli values, as a function of project length. The program uses a cumulative difference algorithm to achieve unit delineation for either deflection and moduli data. The delineation approach is useful for identifying units of sections or stations that present similar structural behavior.

- Print Results of Latest Analysis: This option permits the user to skip directly to the Print Menu in order to obtain summary and/or detailed printouts of the last analysis performed by the Modulus Backcalculation program.

To finish a session, just select option five to exist to DOS.

3. RUNNING THE APPLICATION PROGRAMS

The FWD Conversion Program

Typically, when a section of road is evaluated using nondestructive testing, the section is divided into stations. The falling weight test, referred to hereafter as a drop, is then performed at each of these stations, as many times as it is required, and the resulting deflection and load information is stored on a computer disk file. The software to perform this is supplied by the FWD supplier. In MODULUS a .FWD extension is used to denote files containing raw FWD deflection data for any highway.

The format used in the Dynatest FWD files is highly elaborate and most of the information that they contain is not relevant to the programs contained in the TTI MODULUS Analysis System. Consequently, a program capable of extracting the specific data was developed.

The first option in the Main Program Menu accesses the FWD conversion program. This program extracts the following variables from a FWD file: district number, county number, highway prefix and number, mile point position of the station (to 3 decimal places).

Load, and deflection readings (up to seven) for a pre-specified drop along the length of a project. The program then stores this information in a new file and appends to its name the extension .OUT. These files form the actual input to the Modulus Backcalculation program and are hereon referred to as INPUT or OUT files. In general, during FWD testing; one or more drops are made at one location. This program can handle for one to eight drops per location. The user will be required to select one for processing.

To start the FWD conversion program, select option one from the menu and press <ENTER>. A window will appear in the lower part of the screen asking you to verify your choice. Enter <Y> if the choice is correct.

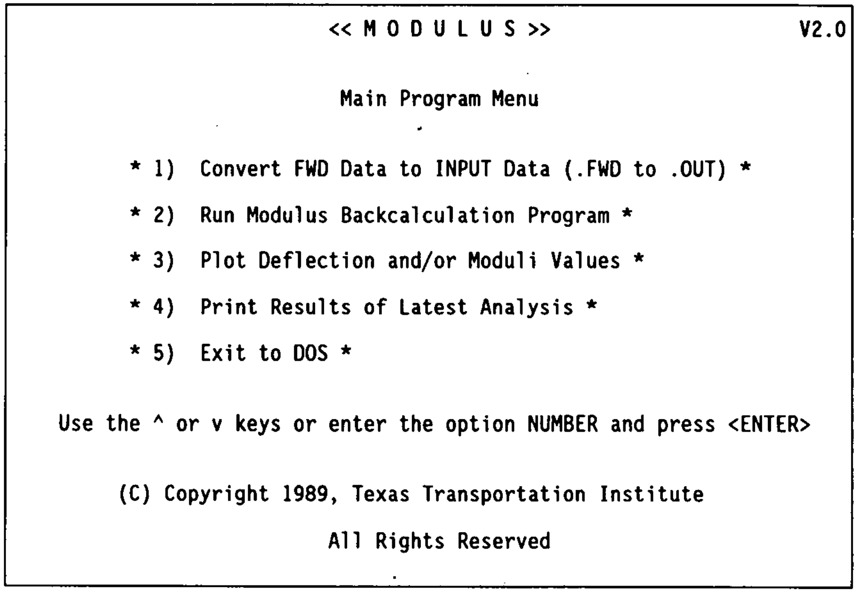
After a few moments, the program input screen (Figure F2) is displayed. There are five fields of required information that the user needs to input before the program can run. These are:

- DRIVE WHERE THE FWD FILE RESIDES: Enter the letter identifier of the drive where the FWD file to be converted is stored. If the FWD file is in the hard disk, enter the letter of the drive from which the program is running. If the file resides in a floppy dis, enter the letter of that drive. Finish this input by pressing <ENTER>.
- FWD DATA FILENAME: In this field enter the name of the FWD file to be converted. Enter the name of the file, up to eight alphanumeric characters, without entering the extension name (it will be automatically appended to the name you entered) and

press <ENTER>. In Texas this filename is a combination of county number and highway name. To see a listing of all. FWD files residing in the selected drive press <F1>. To select a file, use the up/down arrow until the desired file is highlighted, then press <ENTER>.

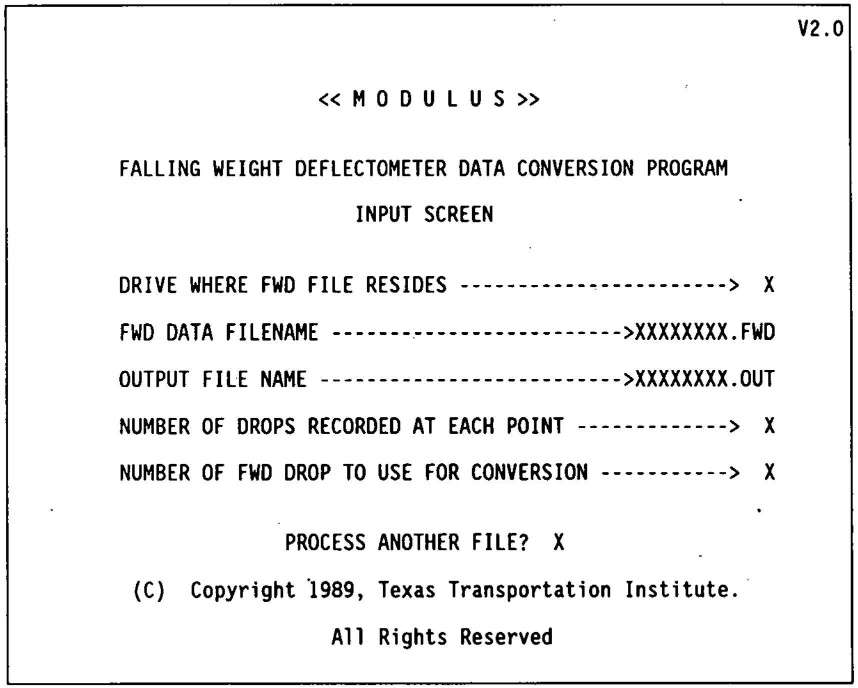
- OUTPUT FILE NAME: Supply the name of the output file. It can also be up to eight charcters long and the .OUT extension will be automatically appended. Again press <ENTER> to finish this input.
- NUMBER OF DROPS RECORDED AT EACH POINT: In this field enter the number of drops (up to eight) performed at each point or station during the test and then press <ENTER>.
- NUMBER OF FWD DROP TO USE AT EACH POINT: At this point, enter the number of the drop to be analyzed. Frequently four drops are recorded at different load levels, e.g., 5,000, 8,000, 12,000, and 15,000 lbs. This option permits the user to select the load level of interest.

Check the input carefully. If a mistake has been made, press the <ESC> key and the cursor will be set back to the beginning of the input process, at the position of the drive letter designator. Press <ENTER> to validate the entries until the incorrect one is reached. To change it, just enter the new value or name and press <ENTER> to validate it. Keep on pressing <ENTER> until the last field is reached. If it is also correct, <ENTER> once again to



```
                  << M O D U L U S >>                        V2.0

                   Main Program Menu

     * 1)  Convert FWD Data to INPUT Data (.FWD to .OUT) *
     * 2)  Run Modulus Backcalculation Program *
     * 3)  Plot Deflection and/or Moduli Values *
     * 4)  Print Results of Latest Analysis *
     * 5)  Exit to DOS *

 Use the ^ or v keys or enter the option NUMBER and press <ENTER>

     (C) Copyright 1989, Texas Transportation Institute
                  All Rights Reserved
```

Figure F1. Main Program Menu.



```
                                                              V2.0

                       << M O D U L U S >>

        FALLING WEIGHT DEFLECTOMETER DATA CONVERSION PROGRAM
                          INPUT SCREEN

        DRIVE WHERE FWD FILE RESIDES -----------------------> X
        FWD DATA FILENAME ------------------------->XXXXXXXX.FWD
        OUTPUT FILE NAME -------------------------->XXXXXXXX.OUT
        NUMBER OF DROPS RECORDED AT EACH POINT -------------> X
        NUMBER OF FWD DROP TO USE FOR CONVERSION -----------> X

                      PROCESS ANOTHER FILE?  X
          (C)  Copyright 1989, Texas Transportation Institute.
                         All Rights Reserved
```

Figure F2. Data Conversion Screen.

validate each entry.

Entering this last <ENTER> will start the conversion process, which should take about 20 to 30 seconds depending on the disk access speed and the length of the file being converted.

When the program has successfully executed, a window with the following message will be displayed:

```
FILE XXXXXXXX.OUT CONTAINS ### POINTS.
```

where XXXXXXXX corresponds to the .OUT file name and ### to the number of points or stations stored in the file.

As a last option, the program will prompt to determine if another file is to be processed. Enter <Y> to extract another FWD file. To quit, <N> and press <ENTER> in order to go back to the Main Program Menu.

To abort this program, press the <ESC> key if the cursor is positioned in the first input field; otherwise press it twice. These <ESC> key sequences will quit the program and return to the Main Program Menu.

Note: If data other than Dynatest FWD data is to be processed then the coding form attached to the end of the user's manual must be used.

Modulus Backcalculation Program

Option two of the Main Program Menu allows the user to run the Modulus Backcalculation program. Inputs to the program consist of a series of default and temporary files, which are transparent to the user. They are created and read automatically. The only file that is user-supplied is the .OUT file, which was created using option one of the Main Program Menu as explained above.

After selecting and validating option two from the menu, the Input/Output information screen (Figure F3) is displayed. In this screen the user is requested to enter the name of the .OUT file (the file created by option one), and the name of the file that will store the deflection information and the corresponding backcalculated moduli values for each pavement layer. This file is referred heron as the OUTPUT file and is given the extension .DAT.

Enter first the name of the INPUT (.OUT) file, up to eight characters long, and press <ENTER>. When the cursor moves to the next field, enter the name of the OUTPUT (.DAT) file, also up to eight characters long. If any changes are required, press the <ESC> key to return to the first position of the first field. If the INPUT file name is incorrect, enter the correct name and press <ENTER>, otherwise press <ENTER> alone. Repeat this procedure for the OUTPUT filename.

After validation of the OUTPUT file name, the program displays the Modulus Backcalculation Menu screen (Figure F4) which allows the user to select any of three alternative ways of running the program or to return to the Main Program Menu.

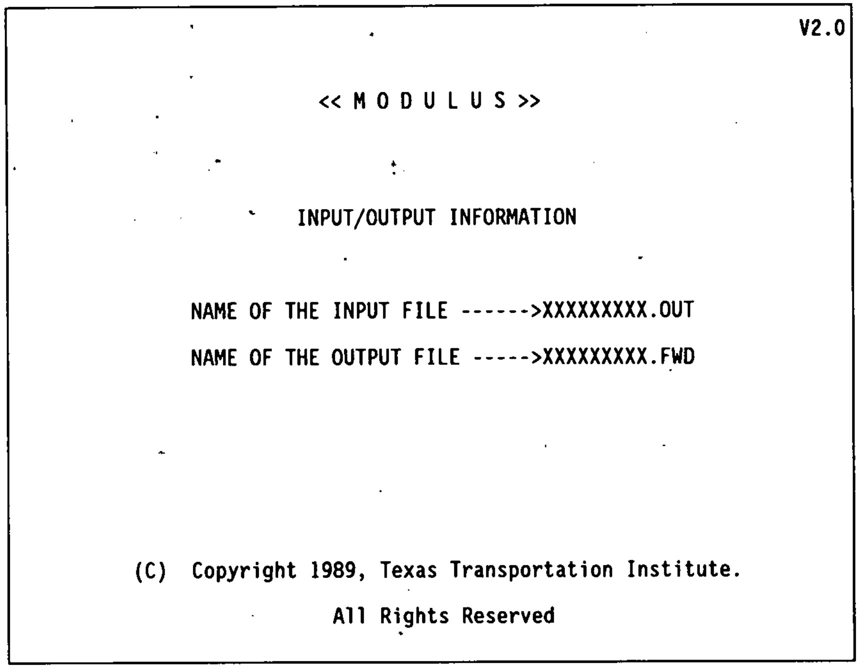
The three options for performing backcalculation are included in MODULUS. They are:

- USE AN ESISTING FIXED DESIGN: This option lets the user select between 24 designs (12 for infinite subgrade and 12 for finite [rigid layer at 20 ft.] subgrade) for which all input parameters, except for the deflection and load values, have been already calculated and stored in disk files. This option provides the fastest analysis since it only has to perform the Search algorithm in the program. In the section "Customizing Fixed Designs", you will find instructions on how to create alternative fixed designs that comply with particular characteristics which are applicable to your needs.
- INPUT MATERIAL TYPES: For this option the user selects the material types, thicknesses for the pavement layers, and test temperature, and the program assigns the range of acceptable moduli and poisson values to be used in the analysis.
- FUN A FULL ANALYSIS: In this option the user supplies all of the input parameters needed to perform the analysis.

To quit the program while in the menu screen, select option 4 to return to the Main Program Menu.

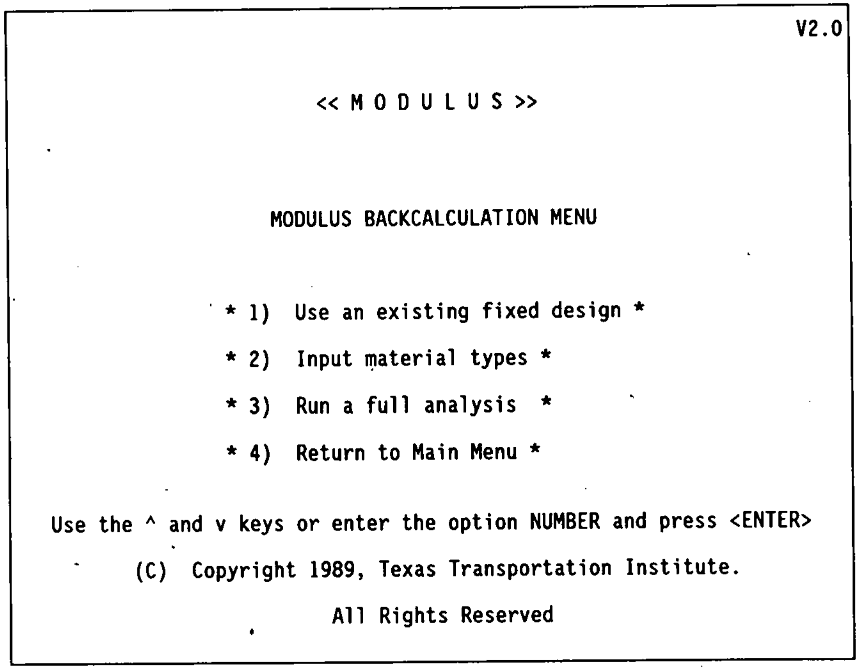
Using the Modulus Backcalculation Menu Options:

The principal difference in the three options of the Modulus Backcalculation menu is that in Option 1, default data bases are used and no runs of the CHEVRON program are required.



```
                                                        V2.0

                        << M O D U L U S >>

                    INPUT/OUTPUT INFORMATION

           NAME OF THE INPUT FILE ------>XXXXXXXXX.OUT
           NAME OF THE OUTPUT FILE ----->XXXXXXXXX.FWD

     (C)  Copyright 1989, Texas Transportation Institute.
                        All Rights Reserved
```

Figure F3. Input/Output File Information.

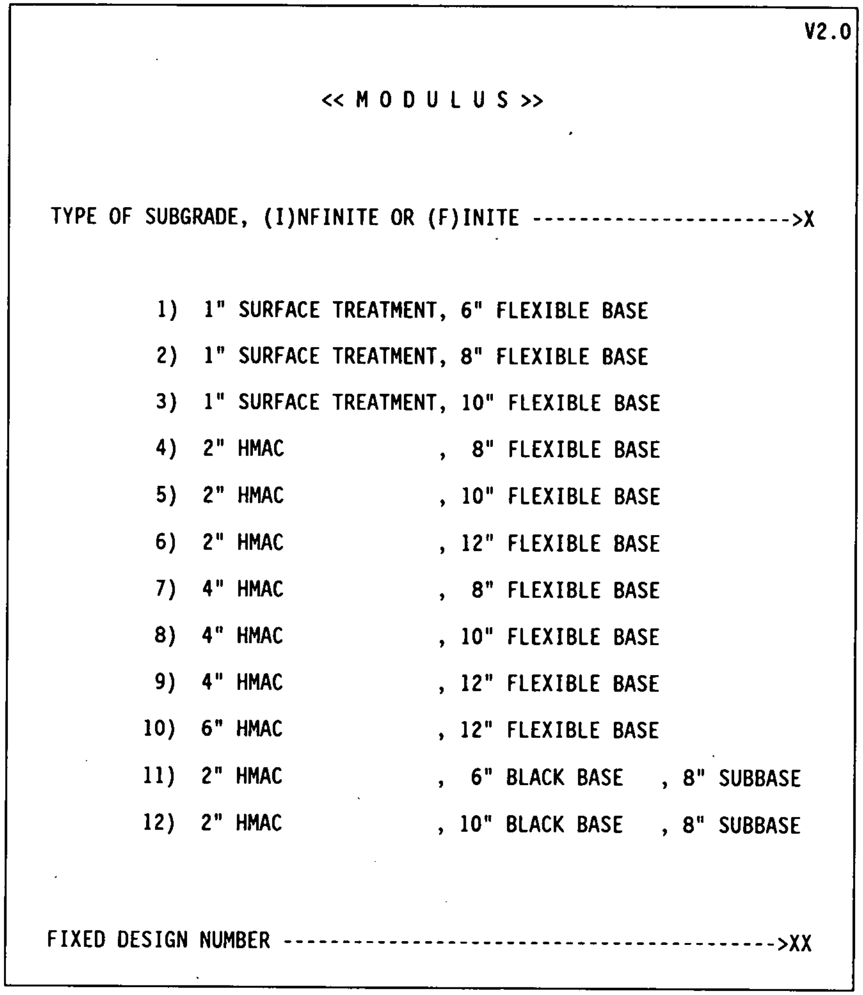


```
                                                        V2.0

                        << M O D U L U S >>

                  MODULUS BACKCALCULATION MENU

                * 1)  Use an existing fixed design *
                * 2)  Input material types *
                * 3)  Run a full analysis  *
                * 4)  Return to Main Menu *

Use the ^ and v keys or enter the option NUMBER and press <ENTER>
     (C)  Copyright 1989, Texas Transportation Institute.
                        All Rights Reserved
```

Figure F4. Modulus Backcalculation Menu.

Option 1 - Fixed Designs: Select this option and the program will display the Existing Fixed Designs screen (Figure F5). These layer thicknesses are common in Texas but can be modified to fit a particular user's need (see section "Customizing Fixed Designs"). The moduli values used to build these default databases are shown in Table F1. The screen presents the user with two prompts: First, select the type of subgrade, infinite or finite (rigid layer at 20 ft.), for the analysis. Enter <F> to use a finite subgrade, or <I> for an infinite subgrade. Pressing <ENTER> after the selection validates the choice and moves to the next prompt. Select one of the 12 available designs by entering the appropriate number and pressing <ENTER>. If no suitable designs are available for the pavement under analysis, press <ESC> twice to return to the previous menu which will permit selection of an alternate backcalculation option.

Option 2 - Input Material Types: When this option is selected, the program prompts for the required information using two separate input screens. The first screen (Figure F6), displays default settings for the FWD machine and four input fields. The cursor is positioned in the first field. If you want to change the default settings, press <FK2>. Press <ENTER> to move through the fields and make the necessary changes, until the cursor returns to the HMAC surface layer thickness input field. Otherwise enter the surface layer thickness in inches and press <ENTER>. The cursor moves to the second field where the program requests the surface layer

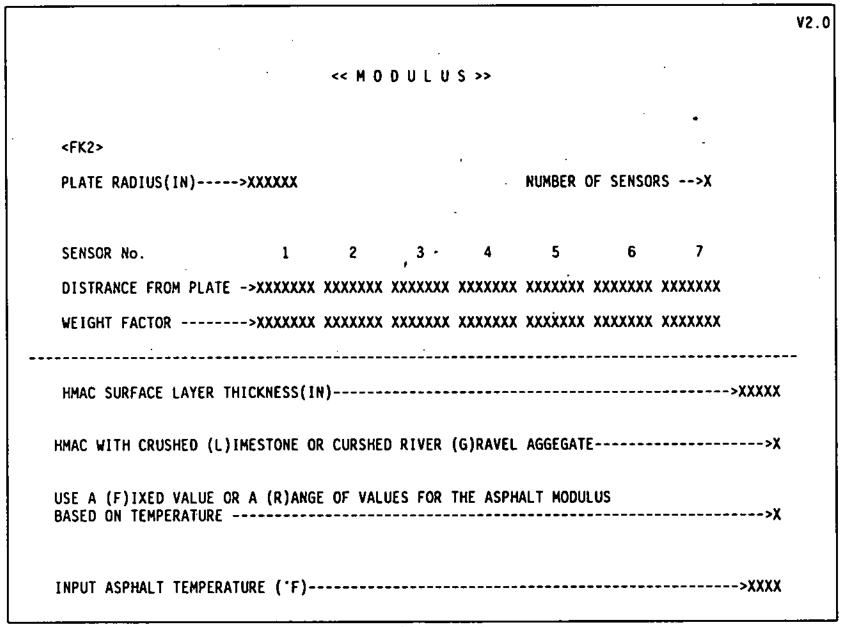


```
                                                                   V2.0

                              << M O D U L U S >>


TYPE OF SUBGRADE, (I)NFINITE OR (F)INITE ----------------------->X


         1)  1" SURFACE TREATMENT, 6" FLEXIBLE BASE
         2)  1" SURFACE TREATMENT, 8" FLEXIBLE BASE
         3)  1" SURFACE TREATMENT, 10" FLEXIBLE BASE
         4)  2" HMAC             ,  8" FLEXIBLE BASE
         5)  2" HMAC             , 10" FLEXIBLE BASE
         6)  2" HMAC             , 12" FLEXIBLE BASE
         7)  4" HMAC             ,  8" FLEXIBLE BASE
         8)  4" HMAC             , 10" FLEXIBLE BASE
         9)  4" HMAC             , 12" FLEXIBLE BASE
        10)  6" HMAC             , 12" FLEXIBLE BASE
        11)  2" HMAC             ,  6" BLACK BASE    , 8" SUBBASE
        12)  2" HMAC             , 10" BLACK BASE    , 8" SUBBASE


FIXED DESIGN NUMBER ------------------------------------------->XX
```

Figure F5. Existing Fixed Designs.

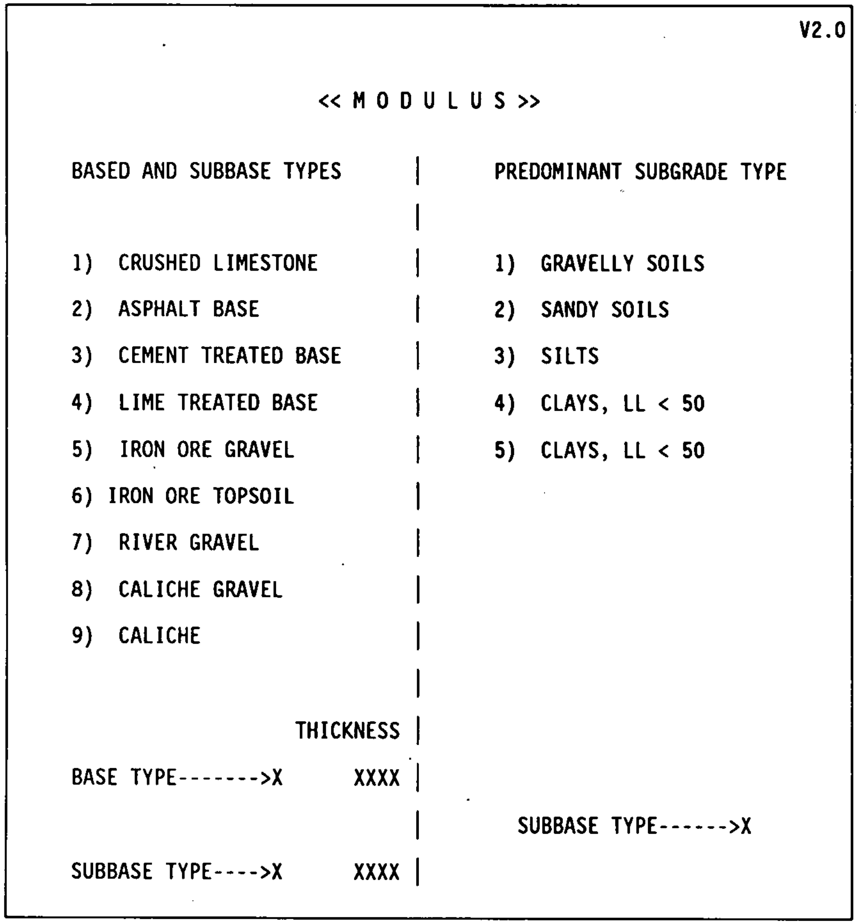
Table F1. Modulus Defaults For the Twelve Fixed Designs (ksi).

Design Number (Figure A5)	Asphalt		Base		Subbase		Subgrade
	Min.	Max.	Min.	Max.	Min.	Max.	
1	500	500	5	100	-	-	15
2	500	500	5	100	-	-	15
3	500	500	5	100	-	-	15
4	500	500	5	100	-	-	15
5	500	500	5	100	-	-	15
6	500	500	5	100	-	-	15
7	200	1200	5	100	-	-	15
8	200	1200	5	100	-	-	15
9	200	1200	5	100	-	-	15
10	200	1200	5	100	-	-	15
11	500	500	200	1200	5	100	15
12	500	500	200	1200	5	100	15



```
                                                                          V2.0

                         << M O D U L U S >>

 <FK2>
 PLATE RADIUS(IN)----->XXXXXX                      NUMBER OF SENSORS -->X


 SENSOR No.               1       2       3       4       5       6       7
 DISTRANCE FROM PLATE ->XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX
 WEIGHT FACTOR -------->XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX
--------------------------------------------------------------------------------
 HMAC SURFACE LAYER THICKNESS(IN)----------------------------------------->XXXXX

 HMAC WITH CRUSHED (L)IMESTONE OR CURSHED RIVER (G)RAVEL AGGEGATE------------->X

 USE A (F)IXED VALUE OR A (R)ANGE OF VALUES FOR THE ASPHALT MODULUS
 BASED ON TEMPERATURE -------------------------------------------------------->X


 INPUT ASPHALT TEMPERATURE ('F)------------------------------------------->XXXX
```

Figure F6. Input Material Types.



```
                                                          V2.0

                      << M O D U L U S >>

    BASED AND SUBBASE TYPES       |    PREDOMINANT SUBGRADE TYPE
                                  |
    1)  CRUSHED LIMESTONE         |    1)  GRAVELLY SOILS
    2)  ASPHALT BASE              |    2)  SANDY SOILS
    3)  CEMENT TREATED BASE       |    3)  SILTS
    4)  LIME TREATED BASE         |    4)  CLAYS, LL < 50
    5)  IRON ORE GRAVEL           |    5)  CLAYS, LL < 50
    6) IRON ORE TOPSOIL           |
    7)  RIVER GRAVEL              |
    8)  CALICHE GRAVEL            |
    9)  CALICHE                   |
                                  |
                        THICKNESS |
    BASE TYPE------->X      XXXX  |
                                  |      SUBBASE TYPE------>X
    SUBBASE TYPE---->X      XXXX  |
```

Figure F7. Input Base and Subgrade Types.

material. Enter <L> for crushed limestone aggregate or <G> for crushed river gragvel aggregate, and press <ENTER> to continue to the next input field. The options to be selected in this field deserve a brief explanation.

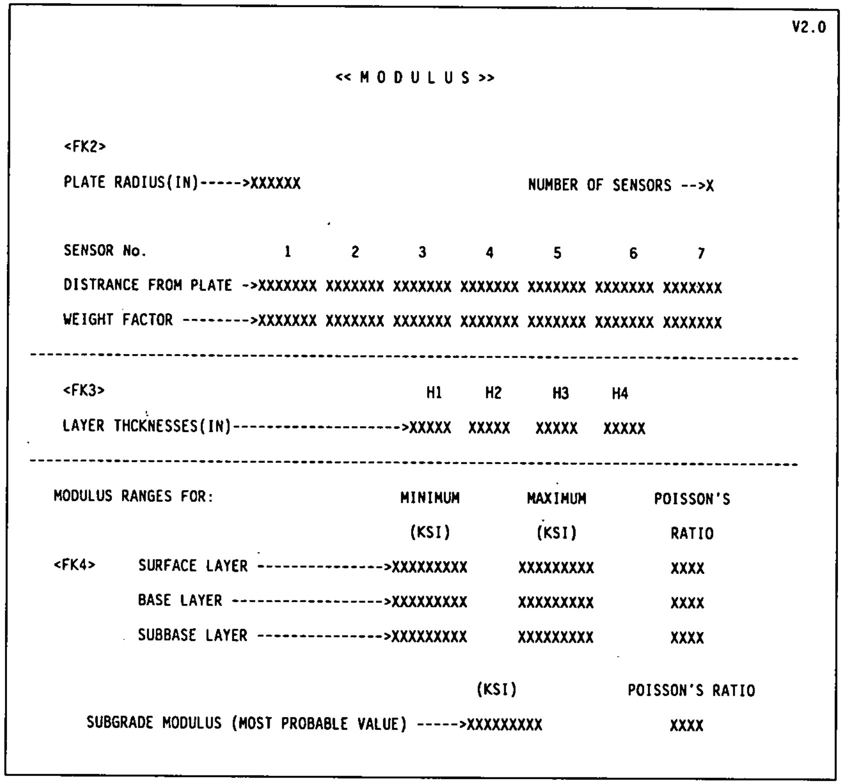
The program has built into it equations for stiffness versus temperature for typical mixes found in Texas (crushed limestone or river gravel mixes). Also, equations which represent the reasonable range of stiffnesses are also available. These were generated by analyzing stiffness results and obtained on rutted mixes (low stiffnesses) and badly cracked mixes (high stiffness). In the backcalculation procedure, if the user wishes to use a fixed default asphalt modulus, which is often the case on these pavements, then a single value is calculated based on the coarse aggregate type and FWD test temperature. However, if an asphalt modulus is to be backcalculated, then an acceptable range of moduli values is generated suing the equation for rutted and cracked mixes, and the FWD test temperature. This option was intended for field personnel who are familiar with materials information but who have limited experience with modulus backcalculation techniques. In this field, select whether you want the program to backcalculate a fixed value or <R> for a range and press <ENTER> or press <FK1> to see the formulas used to each of the two options. The last field in this screen prompts for the pavement temperature in degrees Fahrenheit. Enter the temperature value and press <ENTER>. Use the <ESC> key to return to the first field and make changes, as explained previously.

After validating the pavement temperature with a <ENTER>, the program displays a second screen (Figure F7). In this screen the user selects the material to be used for the base, subase if any, and subgrade of the pavement sections to be analyzed. The input sequence is organized in five fields. In the first field enter any of the nine available base material options. The second field takes the base thickness in inches. If a subbase is present, input its type and thickness as for the base. Enter <ENTER> in the subbase type if there is no subbase. In field number five, enter the type of subgrade as per the option list. Changes to the screen can be made using the <ESC> key as described previously. Press <ENTER> to validate the input and to run the program. This time the message "The Chevron Program is running..." appears in the screen to indicate that the program is executing. When CHEVRON is complete, the data base is generated, and the Path Search algorithm program takes over; the respective message is displayed to indicate that it is executing. Completion of the search phase is confirmed by the "Search program terminated normally!" and "Press any key to continue" messages. Pressing any key leads you to the Print Results Menu.

Option 3 - Run a Full Analysis: This option of the Modulus Backcalculation Menu lets the user specify the thickness, moduli ranges, and Poisson Ratios for up to four layers within a pavement section. When you request this option, the input screen (Figure F8) is displayed. The values that are displayed on the screen are the values used in the most recent run of the program. To run the

program with these values press <ENTER>. The existing values can be edited at three levels which are accessible through function keys two to four. The editing levels correspond to the degree of likelihood in which you would change the values, from less to more likely. For all practical purposes, information such as plate radius, number of sensors, sensor distance to the plate and weight factors are prone to remain the same thorughout the length of a project since these values reflect the characteristics of the FWD, DYNAFLECT, or any other machine used. At this point press the <ESC> key if you want to abort the program. Editing is done in the same way as for the previous programs; that is, you enter the desired value and validate it by pressing <ENTER>.

If you want to change all the values on the screen, press the <fK2> key. The cursor will be positioned in the plate radius field. Enter the plate radius in inches and the number of deflection sensors. Enter the plate radius in inches and the number of deflection sensors. Then enter the spacing of the sensors in inches and the weighing factor to be used for each sensor. For the FWD, a tyhpical plate radius is 5.91 inches with spacings at 0, 12, 24, 36, 48, 60 and 72 inches. For the Dynaflect, a 2 inch plate radius is recommended with a 1000lb load and sensor spacing of 10.0, 15.6, 26.0, 37.3 and 49.0 inches. To change layer thicknesses and modulus ranges press the <FK3> key. In these four fields labelled H1 to H4, enter the pavement thicknesses in inches. H1 represents the surface layer, H2 the base layer, H3 the subbase to year, and H4 the subgrade. For a four layer pavement, enter their thicknesses in their respective fields. In the subgrade field, however, indicate whether the layer is infinite or finite. Enter <0> for an infinite subgrade or the thickness of subgrade to the beginning of the rigid layer in the case of a finite subgrade. For a three layer system with no subbase, enter the surface thickness, the base thickness, then zero <0> to indicate the absence of subbase, and the subgrade information. For a two layer pavement, the procedure is the same except that a thickness of <0> is entered for the base layer.



```
                                                                                V2.0

                              << M O D U L U S >>

  <FK2>
  PLATE RADIUS(IN)----->XXXXXX                      NUMBER OF SENSORS -->X


  SENSOR No.               1       2       3       4       5       6       7
  DISTRANCE FROM PLATE ->XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX
  WEIGHT FACTOR -------->XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX
-------------------------------------------------------------------------------------
  <FK3>                                      H1      H2      H3      H4
  LAYER THCKNESSES(IN)-------------------->XXXXX   XXXXX   XXXXX   XXXXX
-------------------------------------------------------------------------------------
 MODULUS RANGES FOR:                       MINIMUM       MAXIMUM       POISSON'S
                                            (KSI)         (KSI)          RATIO
 <FK4>    SURFACE LAYER --------------->XXXXXXXXX     XXXXXXXXX        XXXX
          BASE LAYER ----------------->XXXXXXXXX     XXXXXXXXX        XXXX
          SUBBASE LAYER --------------->XXXXXXXXX     XXXXXXXXX        XXXX

                                                    (KSI)          POISSON'S RATIO
    SUBGRADE MODULUS (MOST PROBABLE VALUE) ----->XXXXXXXXX             XXXX
```

Figure F8. Full Analysis.

To change the modulus ranges only, press the <FK4> key. Enter the lower modulus boundary value, the upper boundary value, and the poisson value for the surface layer. Then, depending on whether the pavement is a two, three, or four layer system, the sensor will move to the corresponding field showing you to edit the values for the particular layer. Next, enter the most probable modulus value in ksi and the corresponding poisson ration value for the subgrade. After entering the value for the subgrade layer poisson ratio, check all the input values and if necessary, change any values using the appropriate function key and repeat the above process. if satisfied with the input, press <ENTER> to execute the program. The "Chevron Program is Running..." message shoudl now appear on the screen.

When the program is complete, it displays the appropriate message and asks the user to press any key. The Print Results Menu is then displayed and the user can obtain a printout of the analysis results.

Plot Deflection and/or Moduli Values Program

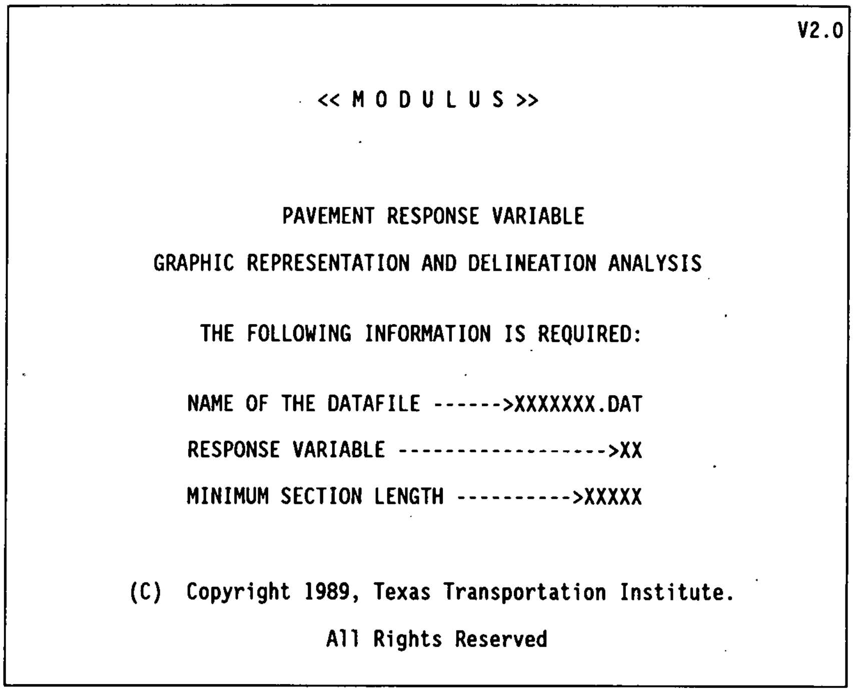
This program allows the user to analyze pavement response variables, mainly deflection readings and calculated moduli values, from a graphical point of view, along the entire project length. It will also perform a unit delineation analysis using the cumulative difference approach in order to identify units of sections having similar characteristics.

To run this program select option three from the Main Program

Menu and press <ENTER>. After validating the choice, the Pavement Response Variable Graphic Representation and Delineation Analysis screen is displayed
(Figure F9). Here, enter the name of the data file containing both the deflection readings and the calculated moduli values for each of the pavement layers. These files are eight characterized by the extension .DAT in their file names; it is automatically appended to the anme of the file that was specified in the backcalculation phase. Enter the file name, up to eight characters long and press <ENTER>.

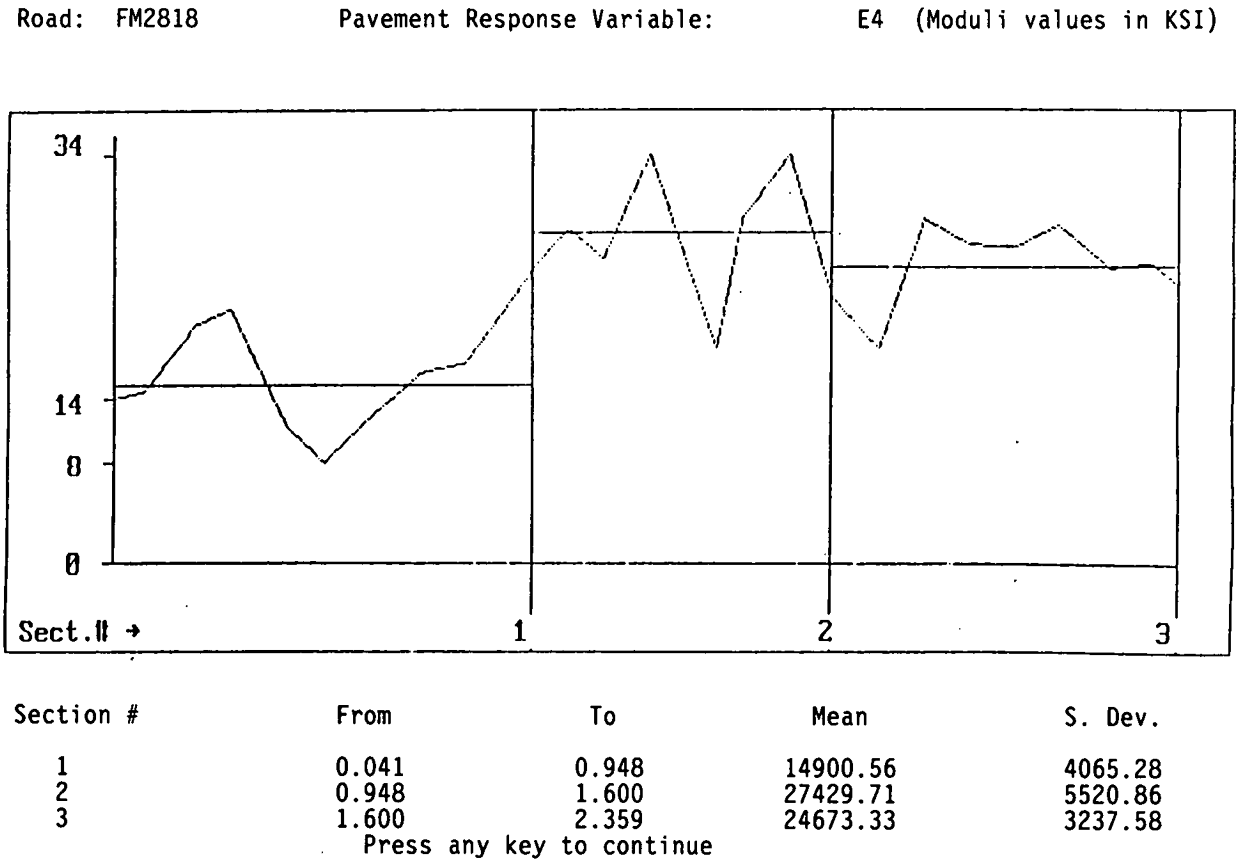
Next, select the response variables to be plotted. There are a maximum of seven deflection readings, and four moduli values for each station. Deflections are identified by a nubmer from 1 to 7, 1 corresponding to the sensor closest to the loading plate, 2 to the second closest, and so on. Moduli values have labels from 8 to 11 where 8 identifies the modulus of the surface layer, 9 the base, 10 the subbase, and 11 the subgrade. Enter the number corresponding to the response variable reqired, 1 through 7 for deflections or 8 through 11 for moduli values, and press <ENTER>.

The last item of information requested is the minimum section length that will be used by the delineation subroutine to perform the unit delineation of the chosen response variable. If consecutive inflection points in the cumulative difference curve for the response variable being analyzed occur at intervals that are less than the minimum section length entered, the program will ignore them. This feature is provided to avoid the clutter of unit



```
                                                        V2.0

                      << M O D U L U S >>


                  PAVEMENT RESPONSE VARIABLE
        GRAPHIC REPRESENTATION AND DELINEATION ANALYSIS

              THE FOLLOWING INFORMATION IS REQUIRED:

           NAME OF THE DATAFILE ------>XXXXXXX.DAT
           RESPONSE VARIABLE ------------------>XX
           MINIMUM SECTION LENGTH ---------->XXXXX


     (C)  Copyright 1989, Texas Transportation Institute.
                     All Rights Reserved
```

Figure F9. Setup For Graphics.



```
Road:  FM2818          Pavement Response Variable:          E4  (Moduli values in KSI)

Section #            From            To             Mean             S. Dev.

    1                0.041           0.948          14900.56         4065.28
    2                0.948           1.600          27429.71         5520.86
    3                1.600           2.359          24673.33         3237.58
                       Press any key to continue
```

Figure F10. Plot For Subgrade Moduli Values For a Section of FM 2818.

delineations that might occur in projects with unusually high response variable variability.

Enter this value in miles including fractions of a mile, that is, as a decimal value, and press <ENTER>. To make any changes, use the <ESC> sequence as in the other programs.

As soon as the <ENTER> key is pressed, the program starts executing and in a few secions the screen is cleared and a plot of the selected response variable as a function of distance along the project is produced (Figure F10). At the bottom of the screen a table of statistics for each of the unit delineations is displayed. If there are more than three delineated sections in the plot, press any key to see the statistics for the reamining sections. Press any key until the message "Would you like to combine sections manually or Quit? (C/Q):" appears. To quit the program at this point enter <Q>, otherwise, enter <C>. The manual combination routine then prompts for the number of sections the user would like the combination to have. Enter the number and press <ENTER>.

To combine all secitons, enter the total number of sections that were delineated in the plot. If the user did not elect to combine all sections, a prompt is displayed asking for the number of the last section to be included as the new section one. The subroutine repeats the last prompt until all of the sections have been accounted for. Then it recalculates and replots the curve showing the new delineations and their respective statistics. Repeat the above sequence for manual combination if there are sections left to combine or quit the program. When the user answers

<Q> to the prompt, the user is given the choice of printing the statistics for the latest delineation. Then, the following prompt is displayed: "Enter <R> to analyze other Responses or <Q> quit to the Main Program Menu:". Selecting <Q> returns to the Main Program Menu while entering <R> redisplays the Pavement Response Variable Graphic Representation and Delineation Analysis screen, allowing the user to select another response variable for graphical analysis.

Print Results Program

The Print Results of Latest Analysis option in the Main Program Menu gives the user direct access to the same Print Results Menu (Figure F11) that is displayed after any of the three options in the Modulus Backcalculation Program terminate execution, and allows the user to print a results summary table or a detailed estimated deflection report, or both for the analysis that was performed the last time the Backcalculation program was used.

The options in this menu are:

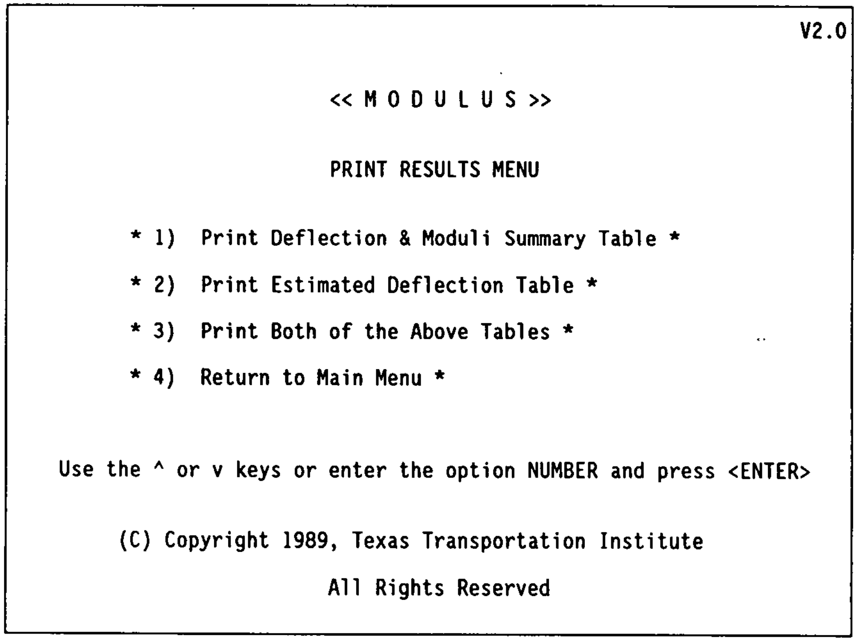
- PRINT DEFLECTION & MODULI SUMMARY TABLE: This option lets the user print a table listing the deflection readings, the calculated moduli values, and the estimated absolute percent error per sensor for each station in the project, with the exception of the ones that do not have a feasible solution to the optimization procedure used in the Modulus Backcalculation program. Also, at the end of the list, statistics are printed for all of the above variables (Figure F12).

- PRINT ESTIMATED DEFLECTION TABLE: Option <2> of the Print Results Menu produces a detailed station by station result report which includes the back calculated deflection values, absolute error and squared error values, force and pressure at the loading plate, and a list of checks indicating if the moduli values are close to the given limits, if the convexity test fails, or if the solution to the particular station was infeasible (Figure F13).
- PRINT BOTH OF THE ABOVE TABLES: This option prints the summary table first, advances the paper to the beginning of a new page, and then prints the detailed section by section report.
- RETURN TO MAIN MENU: It does just that.

Customizing Fixed Designs

The first option is the Modulus Backcalculation menu, "Use an Existing Fixed Design", allows the user to access 24 different pavement design types that are characteristic of Texas. These are divided into two groups, Fixed designs one through twelve and thirteen through twenty four, that differ from each other only in that the first group assumes the existence of an infinite subgrade depth while the latter group assumes a specified depth to bedrock (20 ft).

The process for creating fixed designs is straight forward and includes three steps:



V2.0

<< MODULUS >>

PRINT RESULTS MENU

* 1) Print Deflection & Moduli Summary Table *

* 2) Print Estimated Deflection Table *

* 3) Print Both of the Above Tables *

* 4) Return to Main Menu *

Use the ^ or v keys or enter the option NUMBER and press <ENTER>

(C) Copyright 1989, Texas Transportation Institute

All Rights Reserved

Figure F11. Print Results Menu.

```
                              TTI MODULUS ANALYSIS SYSTEM  (SUMMARY REPORT)

District:  17                                                                                    MODULI RANGE (psi)
County:    21                                                       Thickness (in)          Minimum         Maximum
Highway/Road:  FM2818                                 Pavement:         4.00                200,000       1,200,000
                                                      Base:            10.00                  5,000         100,000
                                                      Subbase:          0.00                      0
                                                      Subgrade:     INFINITY                         15,000

          Load      Measured Deflection (mils):                                 Calculated Moduli Values (psi):                     Absolute %
Station   (lbs)     R1      R2      R3      R4      R5      R6      R7    SURFACE(E1)  BASE(E2)  SUBBASE(E3)     SUBGRADE(E4)  ERROR/Sens

0.041    11,687   31.08   21.43   12.33    7.48    5.06    3.65    3.09    1,135,938     6,996           0            13,760        1.54
0.104    11,999   26.18   17.50   10.28    6.71    4.82    3.52    3.01    1,004,494    16,578           0            14,718        1.76
0.214    11,267   39.88   20.42    9.54    4.89    3.20    2.16    2.01      504,720     5,866           0            19,553        7.50
0.295    12,567   47.95   20.86    8.55    4.53    3.16    2.40    2.01      277,506     7,255           0            21,333        6.49
0.418    11,607   47.14   28.20   15.33    8.73    5.73    4.15    3.41      572,952     5,000           0            11,690        4.45
0.501    11,063   66.70   38.49   19.73   11.60    7.51    5.64    4.78      251,335     5,000           0             8,037        4.61
0.604    11,095   35.98   21.39   11.67    7.64    5.26    3.86    3.25      555,086    10,230           0            12,279        3.56
0.708    12.231   30.52   19.45   10.97    6.75    4.59    3.19    2.61    1,199,997     7,201           0            16,396        4.02
0.803    11,343   12.85   11.10    8.51    6.07    4.27    3.03    2.49    1,199,997    99,999           0            16,496        8.72
0.948    11,167   35.94   16.57    6.62    3.40    2.33    1.78    1.65      365,371     7,666           0            24,837        4.40
1,027    11,967   25.66   11.95    5.06    2.87    2.21    1.82    1.65      283,302    28,330           0            28,330        7.49
1,103    11,999   70.92   25.85    6.33    3.28    2.29    1.66    1.29      271,504     8,145           0            27,150       19.85
1,201    11,527   18.15   11.42    5.59    2.91    1.94    1.45    1.33    1,199,997    10,100           0            33,288        3.45
1,348    11,111   36.22   23.05   11.18    5.50    3.24    2.24    2.05      599,920     5,458           0            18,189        8.29
1,402    11,255   18.67   11.59    5.71    3.15    2.13    1.70    1.53    1,056,640    14,110           0            28,306        1.57
1,508    11,471   14.18    9.32    5.10    3.11    2.25    1.78    1.45    1,199,997    34,628           0            34,236        2.67
1,600    13,535   28.03   16.45    8.47    4.61    2.85    1.99    1.69      978,708     6,866           0            22,888        5.75
1,706    11,823   57.26   28.40   10.97    5.46    3.48    2.32    2.09      271,045     5,421           0            18,068       13.19
1,801    11,031   19.92   12.52    6.21    3.23    2.13    1.66    1.69    1,030,749    11,073           0            27,192        3.92
1,902    11,055   18.99   12.56    6.58    3.64    2.33    1.66    1.57    1,199,997     8,111           0            27,038        5.72
2,006    11,159   17.75   11.42    5.80    3.40    2.33    1.74    1.61    1,199,997    15,180           0            26,803        1.88
2,100    11,127   26.91   14.50    6.58    3.32    2.06    1.53    1.37      694,138     8,373           0            27,913        5.56
2,213    11,695   52.97   23.38    8.71    3.68    2.29    1.70    1.49      300,667     7,400           0            24,661       18.16
2,303    11,431   26.38   15.11    6.70    3.52    2.41    1.91    1.89      605,748    10,349           0            24,512        2.71
2,359    10,999   23.09   13.90    7.03    4.00    2.69    1.91    1.81      980,712     9,868           0            23,154        3.54
```

Figure F12. Summary Listing.

```
                              TTI MODULUS ANALYSIS SYSTEM  (SUMMARY REPORT)

District 17    County : 21                     Distance (in) from center of loading plate to sensor:    R1  =   0.000  Weight Factor   1.0
Highway/Road:  FM2818                                                                                    R2  =  12.000  Weight Factor   1.0
Radius of loading plate (in):     5.910                    POISSON RATIO VALUES                          R3  =  24.000  Weight Factor   1.0
Surface thickness (in):           4.000                       H1:  μ = 0.40                              R4  =  36.000  Weight Factor   1.0
Base thickness (in):             10.000                       H2:  μ = 0.35                              R5  =  48.000  Weight Factor   1.0
Subbase thickness (in):           0.000                       H3:  μ = 0.35                              R6  =  60.000  Weight Factor   1.0
Subgrade thickness (in):        INFINITY                      H4:  μ = 0.40                              R7  =  72.000  Weight Factor   1.0

Station:  0.041            R1        R2        R3        R4        R5        R6        R7            Plate Load      =  11,688 lbs
Measured Deflection:     31.08     21.43     12.33     7.48      5.06      3.65      3.09            Plate Pressure  =  106.520 psi
Calculated Deflection:   30.57     21.78     12.46     7.38      4.94      3.75      3.09
  % ERROR                 1.64     -1.62     -1.02     1.35      2.36     -2.65      0.13            Absolute Sum of % ERROR  =  10.800

Layer:                  SURFACE(E1)      BASE(E2)      SUBBASE(E3)      SUBGRADE(E4)                 Square Error            =   0.002

Moduli Values (ksi):      1,135.9          7.0            0.0              13.8
Close to limits?            NO             NO             N/A               -                        Failed Convexity Test?  NO

Station:  0.104            R1        R2        R3        R4        R5        R6        R7            Plate Load      =  12,000 lbs
Measured Deflection:     26.18     17.50     10.28     6.71      4.82      3.52      3.01            Plate Pressure  = 109.360 psi
Calculated Deflection:   25.85     17.75     10.30     6.55      4.69      3.66      3.02
  % ERROR                 1.27     -1.41     -0.19     2.32      2.75     -3.98     -0.43            Absolute Sum of % ERROR  =  12.400

Layer:                  SURFACE(E1)      BASE(E2)      SUBBASE(E3)      SUBGRADE(E4)                 Square Error            =   0.003
Moduli Values (ksi):      1,004.5         16.6            0.0              14.7
Close to limits?            NO             NO             N/A               -                        Failed Convexity Test?  NO

...CONTINUED ON NEXT PAGE...
```

Figure F13. Detailed Bowl By Bowl Listing.

```
                          TTI MODULUS ANALYSIS SYSTEM  (SUMMARY REPORT)

Station:  0.214           R1       R2       R3       R4       R5       R6       R7        Plate Load      =  11,368 lbs
Measured Deflection:      39.88    20.42    9.54     4.89     3.20     2.16     2.01      Plate Pressure  = 103.600 psi
Calculated Deflection:    36.17    21.38    9.13     4.47     3.02     2.47     2.12
   % ERROR                9.31     -4.68    4.29     8.52     5.69     -14.35   -5.67     Absolute Sum of % ERROR  =  52.500

Layer:                  SURFACE(E1      BASE(E2)      SUBBASE(E3).     SUBGRADE(E4)       Square Error             =   0.047
Moduli Values (ksi):       504.7          5.9            0.0             19.6
Close to limits?            NO            YES            N/A              -                Failed Convexity Test?  NO

Station:  0.295           R1       R2       R3       R4       R5       R6       R7        Plate Load      =  12,568 lbs
Measured Deflection:      47.95    20.86    8.55     4.53     3.16     2.40     2.01      Plate Pressure  = 114.540 psi
Calculated Deflection:    44.50    22.22    8.10 ·   4.14     3.06     2.55     2.18
   % ERROR                7.19     -6.53    5.21     8.65     3.24     -6.31    -8.29     Absolute Sum of % ERROR  =  45.400

Layer:                  SURFACE(E1      BASE(E2)      SUBBASE(E3)      SUBGRADE(E4)       Square Error             =   0.032
Moduli Values (ksi):       227.5          7.3            0.0             21.3
Close to limits?            NO            NO             N/A              -                Failed Convexity Test?  NO

Station:  0.418           R1       R2       R3       R4       R5       R6       R7        Plate Load      =  11,608 lbs
Measured Deflection:      47.14    28.20    15.33    8.73     5.73     4.15     3.41      Plate Pressure  = 105.790 psi
Calculated Deflection:    44.53    29.26    14.88    8.25     5.54     4.32     3.62
   % ERROR                5.53     -3.77    2.91     5.47     3.24     -4.12    -6.09     Absolute Sum of % ERROR  =  31.100

Layer:                  SURFACE(E1      BASE(E2)      SUBBASE(E3)      SUBGRADE(E4)       Square Error             =   0.015
Moduli Values (ksi):       573.0          5.0            0.0             11.7
Close to limits?            NO            YES            N/A              -                Failed Convexity Test?  NO
```

Figure F13. Detailed Bowl By Bowl Listing (Continued).

- Running the "Full Design" option from the Modulus Backcalculation Menu using the parameters for the new fixed design;
- Renaming the TMP.DEF and BIS.REs files produced in the previous step to TMP#.DEF and BIS#.RES respectively, where # stands for the number of the existing fixed design being replaced; and
- Modifying the DEFAULT.DAT file which stores the fixed design menu definitions to reflect the change.

The above procedure has to be duplicated every time a new fixed design is to be incorporated into the system. To replace a new design it is recommended that the infinite and finite depth files be both replaced. For example TMP1.DEF, BIS1.REs and TMP13.DEF and BIS13.RES contain information for pavement type 1 of the fixed design option. Replace both of these with the output from Option three before changing the names in DEFAULT.DAT.

Note the system should be backed up regularly.

NCHRP STUDY 10-27 MODULUS BACKCALCULATION
DATA INPUT FORM USED TO BUILD .OUT FILE

STATE I3	COUNTY I4		HIGHWAY A8	MILEPOST F8.3		LANE	LOAD (lbs.) I6	SENSOR 1 (mils) F6.2	SENSOR 2 (mils) F6.2	SENSOR 3 (mils) F6.2	SENSOR 4 (mils) F6.2	SENSOR 5 (mils) F6.2	SENSOR 6 (mils) F6.2	SENSOR 7 (mils) F6.2
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
				.				.	.	.	.	.	.	.
1 2 3	4 5 6 7	8	9 10 11 12 13 14 15 16	17 18 19 20 21 22 23 24	25	26	27 28 29 30 31 32	33 34 35 36 37 38	39 40 41 42 43 44	45 46 47 48 49 50	51 52 53 54 55 56	57 58 59 60 61 62	63 64 65 66 67 68	69 70 71 72 73 74

APPENDIX G

COMPARATIVE STUDY OF ANALYSIS ERRORS

(See Note under Appendix B, p 49)

APPENDIX H

EXPERT SYSTEM FOR NDT DATA ANALYSIS

Back calculation of pavement layers' effective elastic moduli from nondestructive testing (NDT) deflection measurements is the foundation of the mechanistic approach for evaluating and designing rehabilitation of pavement structures. Various back calculation computer programs have been developed, mostly based on linear elastic theory and employing different deflection-matching algorithms, but none of these programs is guaranteed to give reasonable moduli values for every deflection basin measured. The results given by different back calculation programs may be quite different due to the different algorithms used. Based on a recent study [40], two agencies using the same computer program derived very different back calculation results for the same pavement sections. These difficulties often discourage pavement engineers from using the more reasonable mechanistic approach and lead them to return to the traditional empirical approach.

The reasons that back calculation programs seem to work well in many cases but fail to produce good results in others may be summarized into the following two categories. Firstly, pavement materials consist of a very large range of possible properties which may not always comply well with the linear elastic, homogeneous, and isotropic assumptions used in elasticity theory. The loading conditions of some NDT devices may also be modelled incorrectly. Secondly, in order to back calculate layer moduli from surface deflections, the thickness of each layer, the Poisson's ratio of layer materials, and the depth of the subgrade need to be known, or at least be estimated closely. The accuracy of deflection measurements may be affected by the accuracy and the way the sensors are resting on the rough pavement surface. The moduli of thin surface layers or 'sandwiched' layers are usually difficult to obtain, since surface deflections are often insensitive to changes of the moduli of these layers. Changes of the moduli of subgrade or other thick layers may often mask changes from thin layers. These are the difficulties due to uncertainty of input variables and errors from the basin-matching algorithms. Any of the above non-ideal situations may render the results from purely numerical back calculation schemes unreliable. Researchers or a handful of pavement experts usually rely on their knowledge and other supplemental information to refine their assumptions, detect possible mistakes, or exclude some layers from back calculation by using 'fixed' moduli for thin layers for example.

The results from the comparative study mentioned above [40] also show that a few analysts with specialized or 'private' knowledge can often produce similar and more reasonable results than the less experienced analysts. When these 'experts' encounter deflection basins that do not give reasonable layer moduli through back calculations, they usually make judgments on the validity of the assumptions, correctness of input, and usefulness of results based on their knowledge. This knowledge may be related to the experience of a particular pavement section, or exists in research reports, text books, general experience, common sense, and engineering rules of thumb. These sources of knowledge are often called upon during analysis, especially when the results from numerical back calculations do not seem reasonable, and when estimation

of some input parameters are needed. This kind of knowledge is extremely valuable to pavement engineers who attempt to estimate pavement layer moduli but are often frustrated by the back calculation results.

The need to call upon expert knowledge during routine pavement structural evaluation or overlay design requires easy access to the expertise. Development of expert system technology has made possible the capture of the specialized or 'private' knowledge and incorporate this knowledge with the numerical computation schemes. Thus an expert system can assist field pavement engineers in analyzing pavement deflections and obtaining the effective layer moduli for evaluation and design purposes. This paper describes the development of a such system.

OBJECTIVE AND SCOPE

One of the major problems faced with back calculation from NDT results is the back calculated layer moduli often vary with the assumptions made in preparing the input data which differs to some extent with each analyst's experience. The interpretation of back calculation results also relies largely on the judgement of each analyst. In order to obtain consistent results, the knowledge used by a handful of experienced pavement experts to analyze pavement structures need to be recorded for use by field engineers. This knowledge should be included in a general framework that can be modified easily as better understanding and modelling of the problem develops or new research findings emerge. They should also be easily accessed by any person who attempts to do back calculation, so that both the procedures and results would be standardized. The use of the expert system approach ensures that the back calculation of each and every deflection measurement would be performed based on the same expertise in this field.

The expert system described here does not replace numerical back calculation procedures. Instead, it acts as both a knowledgeable pre- and post-processor. The pre-processor contains such knowledge as what information is needed in preparing input for the back calculation procedures. The post-processor contains knowledge for judging the validity of back calculation results (e.g. if the results are reasonable to the descriptions of pavement layer materials, if there is any contradiction between assumptions and reality, or if the errors between the measured and computed deflection basin shows any sign of nonlinearity, etc...), and provides means of selecting the representative modulus value for design purposes.

A demonstrative prototype expert system for back calculating layer moduli from deflection basins of the Falling Weight Deflectometer (FWD), one of the major NDT devices, has been developed using in-house expertise. Although the system was designed for use with the back calculation program MODULUS [41], it may easily be converted for use with other procedures since the knowledge used in all back calculation programs should be very similar. The aim of the system is to be capable of running on the portable computer that is carried in the FWD vehicle so that the speed of the MODULUS program (each back calculation takes only about one minute) can be fully exploited and field observations and confirmation tests performed if necessary. It thus increases the reliability of results from the NDT testing and back calculation.

BACKGROUND

Knowledge based expert systems (KBES), or expert systems in short, have attracted considerable attention for their ability to solve complicated problems that can not be solved by any existing algorithms but requires heuristic and judgmental knowledge. The expert systems area is a branch of Artificial Intelligence research which, in general, is concerned with how to simulate human intelligence by computer software. In the present, expert systems can achieve close to human expert performance only when given a very specific task to solve so that a narrow range of knowledge is required. The most widely used method of representing domain knowledge in an expert system is the use of production rules. In this method, knowledge is decomposed to many IF <condition> THEN <action> statements. For example, IF the pavement surface temperature is greater than 90 degree F AND the asphalt layer is not aged, THEN the asphalt concrete modulus should be less than 600,000 psi.

The major components of an expert system include the knowledge base, context, inference mechanism, user interface, and sometimes, explanation facility. The knowledge base, which contains the problem solving information of a particular domain, is the most important part of an expert system. The context is where the specific information about the current problem is stored. The inference mechanism searches the knowledge base and the context to find a chain of reasoning that leads to the solution of the current problem. The user interface and explanation facility make the system easier to use.

The major characteristics that differentiate expert systems from conventional computer programs is the separation of the domain knowledge and the control knowledge. Nevertheless, some of the control knowledge, or problem solving strategy, is inseparable from the domain knowledge. It should be included in the knowledge base in order to make the expert system work efficiently. A flow diagram that corresponds to the line of reasoning of how a domain expert solves the problem is often necessary in organizing the knowledge base. A complete decision tree, however, is not required to build an expert system.

The most difficult task in building an expert system is acquiring domain knowledge from a human expert. In the engineering field, much of the knowledge is in procedural forms, still the reasoning for using one analysis method over another and the difference between reality and analytical results requires a substantial amount of 'engineering judgement'. Experts are often unable or hesitate to reveal their rules of thumb or 'private knowledge' on how to deal with difficult problems due to the informality of this kind of knowledge. But this private knowledge is what distinguishes an expert from the rest in dealing with difficult problems. It is suggested [24] that one effective way of acquiring the expert knowledge is through challenging the expert with difficult real domain problems and literally 'watching' him solve these problems, recording every piece of information that is used by the expert. Reviewing and discussing with the expert all of the details in solving these problems may expose much of the expertise. This process is time consuming and requires precious time and cooperation from the expert. Yet it is still the best known way of building a knowledge base. The

back calculation expert system is no exception.

Many expert system development "shells" which provide the inference mechanism, user interface, and explanation facility are available so that users can concentrate on building the knowledge base for their problem domain. A microcomputer based shell called CLIPS [22] was selected for the back calculation expert system due to its high portability, low cost, and easy integration with external programs.

More thorough discussions on principles of expert systems can be found in [23] and [42]. For applications of expert systems in the Civil Engineering area, Maher [24], Kostem [43], Ritchie [44], Hall [45] and Abkowitz [46] are a few good sources.

BUILDING A BACK CALCULATION KNOWLEDGE BASE

The results of back calculation may be used in either project level or network level analysis. Due to the differences in the purpose of these two analyses and the way back calculation results are used, the number of tests and the elaboration of back calculations are different. We shall limit our discussion to the project level analysis only, even though the two analyses share a large part of the knowledge base.

Figure H1. shows a flow diagram of the back calculation expert system for project level analysis. The pre-processing is performed before the field testing. The post-processing has two stages, one during the field testing and one after the field testing. Figures H2. to H3. illustrate the components of the pre-processor and post-processor. These flow diagrams depict a general procedure for back calculating effective

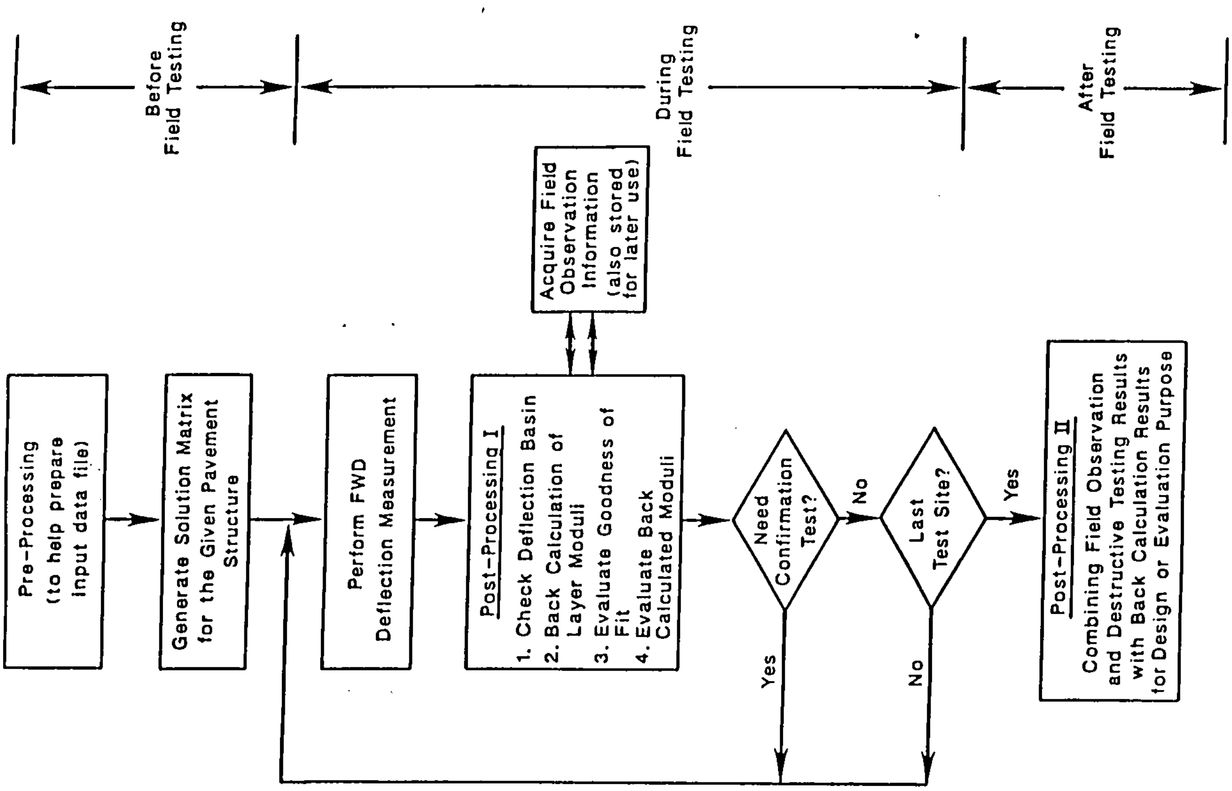


Figure H1. Flow Diagram of the Project Level Back Calculation Expert System

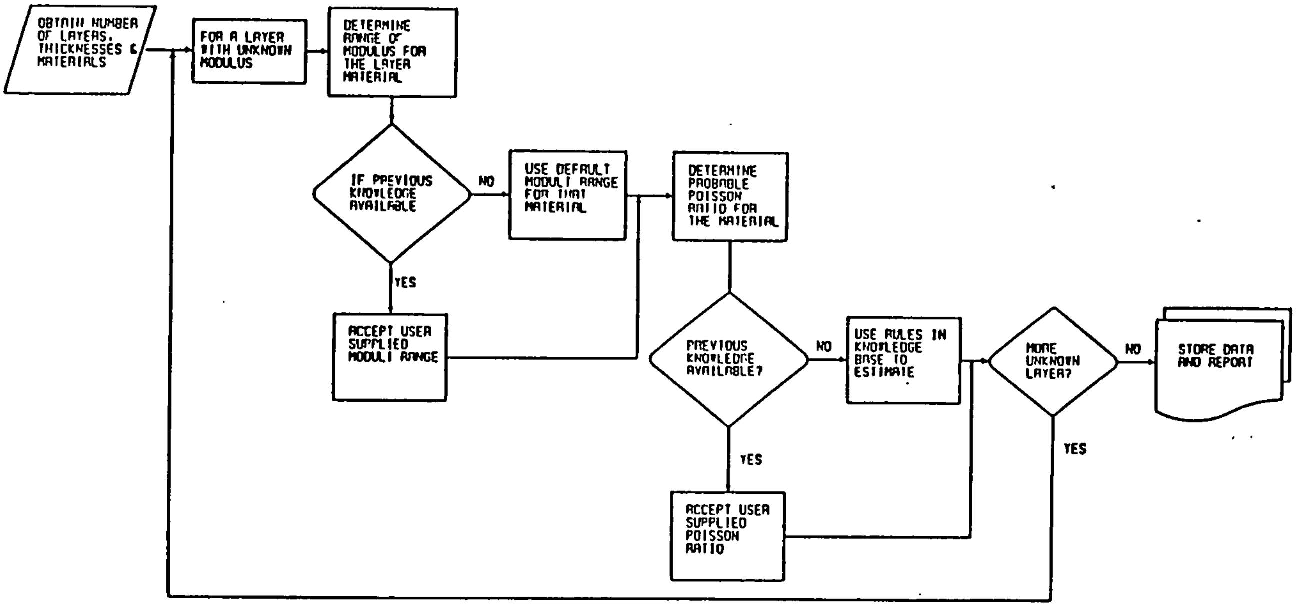


Figure H2. Components and Diagrams of the Pre-processor

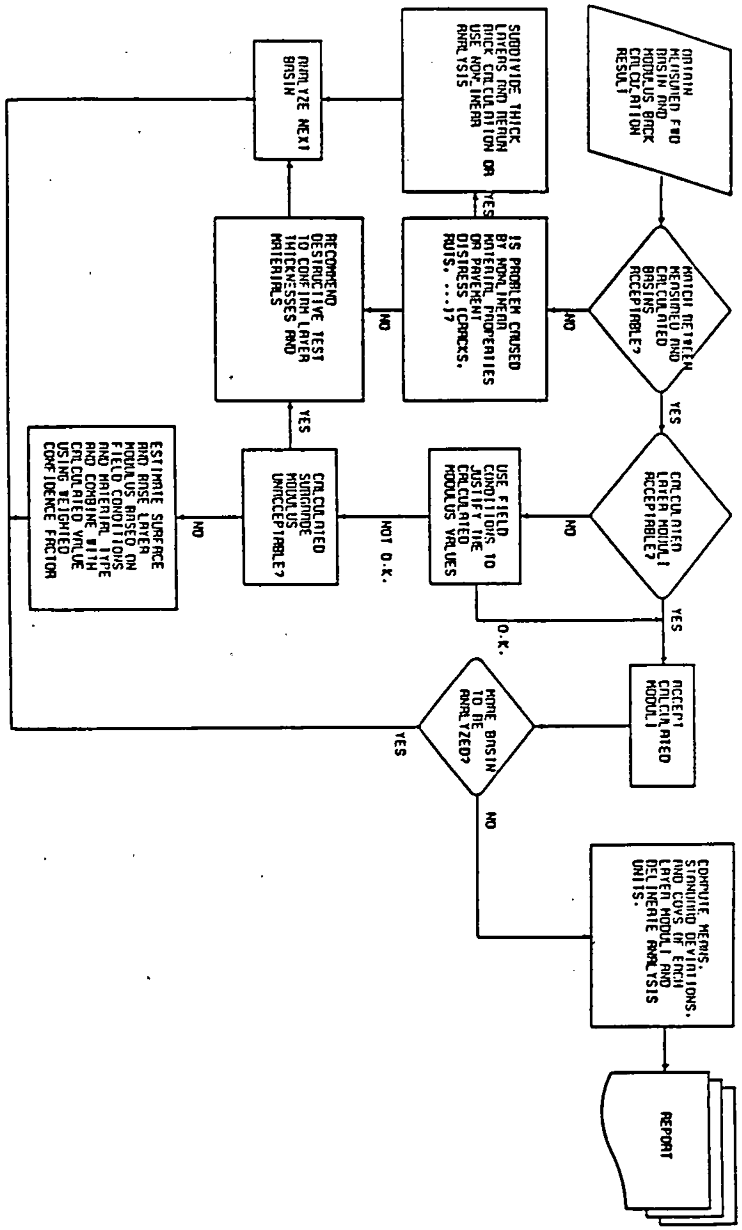


Figure H3. Components and Diagram of the Post-processor

pavement layer moduli from FWD deflection measurements using the computer program MODULUS and the expert system.

The MODULUS program requires the deflection basin database for a given pavement structure (known layer thicknesses, Poisson's ratio and ranges of layer moduli) to be generated and stored before beginning the field testing. It is suitable when a large number of NDT sites with similar pavement cross-sections are to be back calculated, i.e. project level analysis.

Based on user provided information on layer material types, layer thicknesses, temperature, and drainage conditions, existing empirical formulas (41) are employed by PASELS to give the estimated layer moduli. Surface distress conditions observed during deflection testing are then used by PASELS to modify the estimated values. Although these estimated moduli are not very accurate, they represent the pavement engineer's common sense assessment and may be used as yardsticks in evaluating the backcalculated moduli. The estimated modulus of each layer is then compared with the backcalculated modulus. When the two are quite different, every possible reason in the knowledge base will be explored to justify the backcalculated value. If such a reason can be found, the estimated modulus will be modified toward the calculated value. If a destructive testing result is available, it should be used as the estimated value, especially for surface, base, and subbase layers. A rerun of the backcalculation program with revised input may be requested if the original input was incorrect or uncertain. For the MODULUS program, which is a database method, this could mean searching through several pre-generated databases.

The following is a detailed description of the knowledge base developed. The stored knowledge is used to generate data in default of better estimations. If the user has any previous and reliable knowledge of the pavement materials under consideration, this knowledge should be acquired and used in the expert system.

Pre-processing

The knowledge that is required in preparing the input for the MODULUS back calculation program (or any other back calculation program), includes the following:

1. The number of layers and the thickness of each layer.
2. Layer material descriptions or characteristics in order to determine the possible ranges of layer moduli and/or 'seed moduli' for initial values and Poisson's ratios of each layer material.
3. Loading conditions (load level, loading area, etc.), and the number and locations of sensors.

The number of layers and layer thicknesses must be determined by past records or field coring data, and are critical to the results of back calculation. The loading conditions and sensor configurations depend on the equipment used. The most variable part of the input data is the range of layer moduli (or seed moduli for some programs) and assigned Poisson's ratios. The latter usually has a less significant effect on the back calculation results, thus the pre-processing knowledge base would mainly involve the determination of the expected range of layer moduli.

The pre-processing part of the PASELS system relies on the user to supply the number of layers, layer thicknesses, and subgrade depth data. When subgrade depth is unknown, however, a default value of 30 ft (360 inches) is suggested. Since the subgrade depth is usually relatively much greater than the pavement layers, its accuracy of estimation is less crucial to the backcalculated moduli values than the other layer thicknesses are. Unless the actual subgrade depth is much smaller (e.g., one half of) or much greater (e.g., twice) than the default value, the results may not be very different.

If the layer modulus range and Poisson's ratio are not given by the user, the pre-processor estimates the default values according to the layer material characteristics, temperature, or CBR value, if available. If the surface layer thickness is less than 2 inches or the base/subbase layer is less than 4 inches, combining adjacent layers into a single layer or using a fixed layer modulus during backcalculation is recommended. Backcalculated modulus values for thin layers, especially when adjacent to a much thicker layer, may contain large errors and are often questionable.

The possible layer modulus range must be wide enough so that the solution database generated by the MODULUS program includes the solution corresponding to the measured field deflections. The default values are shown in Table H1. For the most probable subgrade modulus required by the MODULUS program, Table H2. is used when no detailed information is given. If the field CBR value is known, it is converted to field modulus by E = 1,500 CBR (for CBR less than 10) or by E = 750 + 750 CBR (for CBR greater than 10).

Wiseman et al., (47) described a knowledge system which used the

Table H1. Default Estimation of Modulus Value for Various Pavement Materials

Material Type	Estimated Modulus Range in ksi Lower Limit	Upper Limit
Hot - Mix Asphalt Concrete	100	1,800
Surface Treatment or Seal Coat	75	800
Portland Cement Concrete	500	5,000
Asphalt Treated Base/ Subbase	50	800
Cement Stabilized Base/ Subbase	500	2,500
Lime Stabilized Base/ Subbase	100	1,500
Untreated Granular Base/ Subbase	5	200

Table H2. Default Probable Subgrade Modulus Values (in Ksi)

	Climatic Condition			
Subgrade Material	Dry	Wet (no freeze)	Wet (freeze-thaw) Unfrozen	Frozen
Clay	15	6	6	50
Silt	15	10	5	50
Silty or Clayey Sand	20	10	5	50
Sand	25	20	20	50
Silty or Clayey	40	30	20	50
Gravel	50	50	40	50

soil classification, environmental conditions (rainfall, depth of water table and drainage situation), and material density to estimate field CBR values of soil. For backcalculation programs other than MODULUS, the range of subgrade modulus may be obtained by using one half to two times the value estimated by the above knowledge system or one third to three times the default value from Table H2.

The default value of Poisson's ratio for each layer is obtained from Table H3, in which the Poisson's ratios of asphalt bound layers are highly dependent upon temperature and are interpolated between the given limits. The degree of cracking of stabilized layers and characteristics of the granular and subgrade materials are obtained from the user.

Based on the above estimations, the input data file for any back calculation program can be prepared. For MODULUS, the deflection basin database can now be generated and stored for later interpolation.

Post-Processing

After the FWD deflection basin has been measured, a quick examination of the basin shape is worthwhile in discovering any malfunctioning of sensors or irregularity (possibly due to large cracking or voids underneath the surface layer) of the measured basin. The subgrade modulus can also be estimated approximately from the deflection basin using a simple method suggested by Ullidtz (21). An external program is called from the expert system to do the analysis, and the operator is prompted for proper actions such as to check the equipment or to look for cracks in the vicinity of the test site.

The MODULUS program is called to search through its previously generated deflection basin database to find a set of layer moduli that

Table H3. Default Values of Poisson Ratio
(Source: AASHTO, 1986)

Material Type	General Range	Values Used in PASELS	
Asphalt Concrete/ Asphalt Treated Base	0.15 - 0.45	$v = (t_p - 30) / 300 + 0.15$	
Portland Cement Concrete	0.10 - 0.20	Severly Cracked	0.30
Cement Stabilized Bases	0.10 - 0.30	Moderately Cracked	0.25
Lime Stabilized Bases	0.10 - 0.30	Crack Free	0.15
		Unknown	0.20
Granular Bases	0.30 - 0.40	Crushed Stone	0.30
		River Gravel/Sands	0.40
		Unknown	0.35
Subgrades	0.30 - 0.50	Clay	0.45
		Silt	0.42
		Silty/Clayey Sand	0.40
		Sand	0.35
		Silty/Sand Gravel	0.33
		Gravel	0.30

best fit the measured deflection basin. The back calculated moduli and the corresponding deflection basin are stored sequentially for later submission to the post-processing part of the PASELS system.

The goodness of match between the measured and computed deflection basin is examined. One rule in the knowledge base states that if the averaged percentage error per sensor is greater than 10 percent and the percentage error of any single sensor is greater than 30 percent then the match is unsatisfactory. The lack of a good match of the deflection basins may indicate a strong effect of non-linear material properties. It could also indicate, however, that the layer thicknesses input or deflection measurement may be incorrect. To ascertain these assumptions, a confirmation test to alleviate the possibility of large measurement error is suggested.

Disagreement of the back calculated layer modulus and the commonly accepted value of the described layer material (i.e when the back calculated modulus reaches the limit set in the pre-processing) may indicate errors in the back calculated modulus or a local deficiency of the layer material. Notification of the operator to inspect the field conditions (drainage condition, surface distress, ... etc.) and to make a confirmation test is an important feature of the system. Closer examination may provide valuable information not only for explaining back calculation results but also for later evaluation and design purposes. Empirical estimations used by the PASELS system to assess the credibility of the backcalculated moduli are as follows (Chou et al.,):

1. For Asphalt Concrete (AC) Modulus

The AC modulus is highly dependent on the temperature. The asphalt layer temperature at a depth of one third of its thickness can be estimated by the measured air temperature as follows (Witczak, 48):

$$T_{ac} = T_{air} [1 + 1/(4+H_{ac} /3)] - 34/(4 + H_{ac} /3) +$$

where T_{ac} and T_{air} are asphalt layer temperature and air temperature, respectively;

H_{ac} is the thickness of AC layer.

The possible asphalt moduli corresponding to the temperatures are computed using the following empirical relationships:

(1) Asphalt Institute equation (Shook et al., 49):

$$\log | E^* | = 5.553833 + 0.028829 \left(\frac{P_{200}}{f^{0.17033}}\right) - 0.03476 (V_v)$$

$$+ 0.070377 (n_{70^oF,\ 10^6}) + 0.000005 [t^{(1.3+0.49825 \log f)} P_{ac}^{\ 0.5}]$$

$$- 0.00189 \left[t_p^{(1.3+0.49825 \log f)} \frac{P_{ac}^{\ 0.5}}{f^{1.1}} \right] + 0.931757 \left(\frac{}{f^{0.02774}}\right)$$

where $|^* E|$ = dynamic modulus (stiffness) of AC, psi (kPa / 6.8948)

P_{200} = percent aggregate passing no.200 sieve

f = frequency, Hz

V_v = percent air voids

$n_{70^oF,10^6}$ = absolute viscosity at 70^oF, poises x 10^6

P_{ac} = asphalt content, percent by weight of mix

t_p = temperature, °F (1.8 °C + 32)

The following default values are used in the above equation: percent passing no. 200 sieve = 6%, air voids = 7%, asphalt content = 5%, viscosity = 10^6 poises, and frequency f of 25 Hz. These default values can be modified by the user if more accurate data is available.

(2) By the Witczak's Equation (Witczak, 48):

$$E_{ac} = \frac{3.8\ 10^6}{1.0046^{T^{1.45}}}$$

where T is the average AC layer temperature in °F

(3) By the Texas Transportation Institute's Equation (Scullion and Chou):

The Texas Transportation Institute recognizing the influence of aggregate interlocking on the AC modulus developed the following equations:

a. If the aggregate used in the AC is crushed stone:

$$E_{ac} = 10^{(6.429 + 0.007909\ T - 0.0003295\ T^2 + 1.47\times10^{-6}\ T^3)}$$

b. If the aggregate used in the AC is river gravel:

$$E_{ac} = 10^{(6.237 - 0.001619\ T + 9.15 \times 10^{-6}\ T^2 - 1.17\times10^{-6}\ T^3)}$$

where E_{ac} = surface modulus in psi

T = mean layer temperature in °F

Based on the above three empirical estimations, a probable range is determined. The lower limit of the probable range is 20% lower than the smallest value among the three estimation, and the upper limit is 20% higher than the largest estimated value. If the backcalculated AC modulus is between the upper and lower limits, then it is considered acceptable. Otherwise, justification is required based on surface distresses, aging effect, and underlying layer material.

2. Granular base materials

Granular materials may exhibit highly nonlinear behavior. In this program, the back calculated layer modulus for the granular base layer is an 'equivalent' linear elastic modulus. The knowledge base uses the average value from the following empirical methods to estimate the effective granular layer modulus.

(1) The Shell method (Smith and Witczak, 50):

In this method, the granular base modulus E_2 is dependent on the subgrade modulus E_{subg} and layer thickness:

$$E_2 = 0.2\ (\ 25.4\ h_2\ )^{0.45}\ E_{subg}$$

where h_2 is the thickness of the base layer in inches.

(2) The Corps of Engineers method (Smith and Witczak, 50):

In this method, the ratio between the granular base modulus and the subgrade modulus is related to material quality and layer thickness as follows:

for subbase or medium quality material: R = 1 + 1.5 h/20
for base or good quality material: R = 1 + 3.4 h/20
for poor quality materials: R = 1

where h is the granular layer thickness in inches, and
R is the ratio between granular base modulus and subgrade modulus.

3. Stabilized base materials

The modulus of the stabilized base material depends on the type and amount of binder and the material stabilized. For asphalt stabilized materials, the knowledge base for the asphalt mixes is used. For lime stabilized material, a modulus range of 100,000 to 1,000,000 psi is suggested. For cement stabilized material, a range of 300,000 to 4,000,000 psi is suggested. In both cases, if it is known that the stabilized layer is cracked then a minimum value of about half of the above minimum value is suggested.

If the back calculated moduli of one or more layers are not within the commonly accepted range, the following is considered:

1. If the field observation indicates poor drainage conditions, or surface distress (e.g. cracking or rutting) exists, low moduli of base and surface layers are possible. The result from destructive testing may be used to verify the under surface deficiency.
2. If the layer modulus underneath a stabilized layer is too low and pavement surface temperature is high, say > 90° F, then it may be caused by the warping of the stabilized layer. Performing testing when pavement temperature is lower than 60° F or moving the loading point so as not to be above the crown of the warp could validate or reject this hypotheses. The same problem can occur when the temperature is too low, say < 40° F, when the warping will be due to a cooler top surface of the stabilized material.
3. For surface layers, especially those with less than 3 inches thickness, or for thin layers between two thick layers, the calculated layer moduli are less reliable due to their modest effect on the surface deflections. If the calculated modulus is too high, the measured field temperature and the Asphalt Institute equation are used instead to determine the AC layer modulus.

If the moduli values are within the range, but the match between the calculated and measured basin is not satisfactory, even after the confirmation tests, the following knowledge is applied:

1. If the pavement structure includes a thick granular layer, which could be highly nonlinear, subdivide these layers and rerun the back calculation.
2. If the results from the above are not satisfactory, nonlinear analysis using the finite element method should be considered. If this type of analysis is not available, a human expert should be consulted.

In project level analysis, where the accuracy of back calculated layer moduli is crucial, destructive testing should be performed to verify the layer thickness, material type and conditions. The results of the back calculations are used to determine the locations of such test. Both locations at which the back calculation results are acceptable and unacceptable are suggested. If the excavation of the pavement reveals a different layer thickness or material type than that which was assumed, back calculations should be rerun with revised input.

After all of the above reasoning and justification, each backcalculated modulus value is then given a weighted confidence factor based on two criteria: first, how well does the computed basin match the measured one, and second, how good is the agreement between the backcalculated modulus and the estimated modulus. The computed value and estimated value are then combined to give a rational estimate of the modulus according to the following formula:

$$E_i = WF_i * E_{icomp} + (1 - WF_i) * E_{iest}$$

where E_i = Rational estimate of layer i modulus

E_{icomp} = Backcalculated layer i modulus

E_{iest} = Empirically estimated layer i modulus

WF_i = Weighted confidence factor, and

$$WF_i = f_1 \ f_2$$

in which f_1 = factor depending on the size of the error in matching the surface deflection

f_2 = factor depending on the difference between the computed and estimated modulus, and agreement with observed condition such as surface distresses

Factor f_1 is introduced due to the situations where the surface matching error is so large that the backcalculated moduli should not be trusted. Factor f_2 is introduced due to the fact that the search scheme may arrive at unreasonably high or low modulus values for thinner layers even though the surface matching error is tolerable. Both factors f_1 and f_2 are defined by quadratic functions. Factor f_1 is defined as:

$$f_1 = \sqrt{1 - \left(\frac{e}{e_{max}}\right)^2}$$

where e = averaged per sensor matching error

e_{max} = per sensor matching error tolerance, usually 10 percent

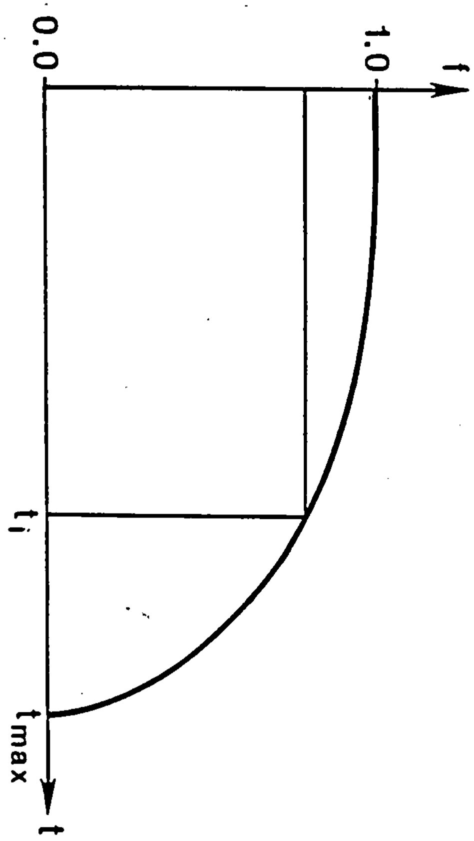
Factor f_2 is defined as:

$$f_2 = \sqrt{1 - \left(\frac{r - 1}{t - 1}\right)^2}$$

where r = ratio between the computed and the estimated modulus with the larger one as the numerator, always greater than 1

t = selected maximum value of r, usually between 2 to 3

The user can select the values of e_{max} and t in the above equations in order to produce the desired shapes of the quadratic functions.



$$f = \sqrt{1-(t_i/t_{max})^2}$$

Figure H4. Typical Shape of the Factors f_1 and f_2

Default shapes of the two functions, f_1 and f_2, are shown in Figure H4.

Due to the variation of paving material properties, it is often necessary to make a number of FWD measurements within a design section. Statistical quantities such as sample means, standard deviations, and coefficients of variation (COV) are used to determine the overall design section parameters. The rational estimation of layer moduli is more appropriate than the backcalculated moduli in applying these statistical measures because the statistical method includes the underlying assumptions that every sample should be equally trustworthy (random errors only). The backcalculated moduli, without being adjusted for the errors with which they are associated, may contain systematic errors and thus are unsuitable for direct statistical inference (Chou and Lytton, 40).

When field testing is completed and field conditions documented, the deflection data and back calculation results can be thoroughly evaluated.

1. In project level analysis, where the accuracy of back calculated layer moduli is crucial, destructive testing should be performed to verify the layer thickness, material type and conditions. The results of the back calculations are used to determine the locations of such tests. Both locations at which the back calculation results are acceptable and unacceptable are suggested. If the excavation of the pavement reveals a different layer thickness or material type than that which was assumed, back calculations should be rerun with revised input.
2. If the match between the calculated and measured basin is not satisfactory, even after the confirmation tests, the following knowledge

is applied:

(1) If the pavement structure includes a thick granular layer, which could be highly nonlinear, subdivide these layers and rerun the back calculation.

(2) If the results from the above are not satisfactory, nonlinear analysis using the finite element method should be considered. If this type of analysis is not available, a human expert should be consulted.

3. If the back calculated moduli of one or more layers are not within the commonly accepted range, the following is considered:

(1) If the field observation indicates poor drainage conditions, or surface distress (e.g. cracking or rutting) exists, low moduli of base and surface layers are possible. The result from destructive testing may be used to verify the under surface deficiency.

(2) If the layer modulus beneath a stabilized layer is too low and the pavement surface temperature is high, say > 90° F, then it may be caused by the warping of the stabilized layer. Performing NDT testing when the pavement temperature is lower than 60° F or moving the loading point so as not to be above the crown of the warp could validate or reject this hypotheses. The same problem can occur when the temperature is too low, say < 40° F, when the warping will be due to a cooler top surface of the stabilized material.

(3) For surface layers, especially those with less than 3 inches thickness, or for thin layers between two thick layers, the calculated layer moduli are less reliable due to their modest effect on the surface deflections. If the calculated modulus is too high, the measured field temperature and the Asphalt Institute equation are used instead to determine the asphalt concrete layer modulus.

4. Delineation of design units and design values are determined using procedures suggested by the AASHTO pavement design guide [2].

CURRENT STATUS AND FUTURE WORKS

Current Status

The prototype expert system currently has not included all the existing expertise, but contains a subset of the knowledge. The knowledge base is divided into separate modules to allow modifications. The expert system acquires the user supplied information through a interactive query and answer session. The user can use the explanation facility to ask why such information is needed or how the conclusion is reached. The back calculation system is able to reason with uncertain knowledge. Each rule in the knowledge base has a confidence level assigned by the expert. The user is often queried to supply the level of certainty along with their qualitative answers.

The prototype expert system is currently programmed to run on an IBM or compatible personal computer. It is constantly being tested against human expert. Figure H5. shows two examples of the rules contained in the knowledge base.

Future Works

1. The usefulness of an expert system depends on its demonstrated performance and reliability. Good performance may be achieved only through a continuous cyclic process of field testing, evaluating results, revising the knowledge base, and more field testing. Such a careful verification process is necessary before the prototype system can become a production system.
2. More information is needed to deal with the material's non-linear properties, and as better methods of determining rock bottom depth and layer thickness evolves, the knowledge base should be revised.
3. The back calculation expert system may be expanded to include distress survey data and other functional performance information to become a pavement evaluation expert system.
4. As the state of expert system technology advances, it is possible to incorporate the ability of 'learning' into this expert system so that the system performance may increase with time. For now, the human expert is still the best at synthesis experience.

Example 1.

```
(defrule Ask-know-layer ""
  (declare (salience 9100))
  (not (data_ready))
  (layer-number known)
  (nlayer ?nl)
  (thickknown ?x)
  (not (Erangeknown ?x))
  (Erangeknown ?y&=(+ ?x 1))
  =>
  (printout crlf " Do you know the probable modulus range of layer " ?x )
  (bind ?ans (read))
  (while (eq ?ans why)
         (printout crlf " If you can give a probable modulus range,
         answer yes,")
         (printout  " otherwise, the system will try to estimate it for
          you. ")
         (bind ?ans (read)))
  (assert (know-modul ?ans)))
```

Example 2.

```
(defrule modl-estim ""
  (declare (salience 7900))
  ?rem0 <- (know-modul N | No | n | no)
  (not (Erangeknown 1))
  (Erangeknown 2)
  =>
  (retract ?rem0)
  (printout crlf " What is the highest air temperature? ")
  (bind ?ans (read))
  (while (eq ?ans why)
         (printout crlf " We are trying to use temperature to estimate
          AC modulus" )
         (printout crlf " Please give an estimated highest pavement
          temperature\(80< t <140\) ")
    (bind ?ans (read)))
  (assert (maxairtemp ?ans))
  (printout crlf " What is the lowest air temperature? ")
  (bind ?ans (read))
  (while (eq ?ans why)
         (printout crlf " We are trying to use temperature to estimate AC
          modulus")
         (printout crlf " Please give an estimated lowest pavement
         temperature\(0< t <50\)")
    (bind ?ans (read)))
  (assert (minairtemp ?ans)))
```

Figure H5. Examples of Rules in the Knowledge Base

SUMMARY

Even though the name 'back calculation' seems to infer a purely numerical computation scheme, it usually takes more than that to obtain effective pavement layer moduli due to the difficulties in modelling the pavement materials.

An expert system which contains the knowledge of a pavement expert in estimating effective layer moduli from NDT deflection measurements could greatly benefit many practicing engineers.

The expert system acts as a pre- and post-processor to the back calculation program, and is able to evaluate back calculation results.

The knowledge base of the expert system is divided into separate modules so that it can be revised easily as new knowledge emerges. Different back calculation programs can be adopted.

USERS GUIDE FOR THE PASELS SYSTEM

Preliminary Version, 4/16/1989

1. Starting-up

To run the PASELS system on a IBM-compatible micro-computer , a hard disk storage is required. Create a subdirectory (say, 'PASELS') on the hard disk, and copy all the files on the two distribution diskettes into that subdirectory. Type CLIPS to invoke the CLIPS environment. Once within the CLIPS, type:

```
(load "prepave.clp")  <-- this loads and compiles the
                           source code of the pre-processor
(reset)               <-- initialize the system (assert
                           initial facts)
(run)                 <-- starts execution of the rules
```

The expert system program is interactive, prompt-driven, and (almost) self-explanatory. Running the preprocessor generates a input data file, namely 'MODIN.DAT', to the MODULUS backcalculation program.

After successfully running the prep.clp, exit the CLIPS environment by typing:

```
(exit)                <-- leave the CLIPS environment
```

While at the DOS prompt type MODULUS to activate MODULUS.BAT, which contains three steps: DATAGEN, BISAR, and SEARCH. The DATAGEN program reads necessary input from the "MODIN.DAT" file. The BISAR program then generates a database of solutions for the given pavement structure. The

SEARCH program reads consecutive deflection basin(s) from FWD.DAT and searches for the set of layer moduli that minimize the sum of errors between computed and measured surface deflections.

After MODULUS has terminated, with backcalculation results stored in the file "SEARCH.OUT", the post-processing part can be called upon, type:

```
clips                      <-- invoke CLIPS environment
(load "pave.clp")          <-- load post-processor and compile
(reset)
(run)
```

The post-processor examines every basin that has been backcalculated and compares the resulting layer modulus values with values that are estimated empirically. If the computed value appears out of normal range, a weighted estimation is suggested. A report is generated that considers the overall success of the backcalculation for the pavement section.

The unit of modulus values is ksi (kilo-lbs per square inch) and unit of layer thickness is inch. The errors between the measured and the computed deflections at sensor locations are expressed in percentage of the measured value, and the total error is in terms of averaged absolute percentage error per sensor.

To obtain a hard copy of the screen dialogue session and evaluation report, press <Ctrl-Print Screen> after the (reset) command .

Note that CLIPS is case sensitive, lower case letter should be used in all the CLIPS commands. User response to the PASELS prompt, however, does not require using a particular case.

If the system stalled during execution -- usually due to unrecognized input -- type "(exit)" will always get you out of the system.

2. Other Commands

One of the major differences between expert system programs and traditional algorithmic programs is that the steps to reach the solution may be different each time depending on the input data. To avoid the feeling of being answered by a "black box", the following CLIPS commands allows user of the PASELS system to trace the reasoning process that leads to the final conclusion:

(facts)	<-- Displays all facts stored in the fact list, use after conclusion has been reached
(watch facts)	<-- Display all fact assertions and retractions, use before the (run) command
(watch rules)	<-- Display all rule firings, use before the (run) command
(unwatch <item>)	<-- Deactivate the above watch command. Example: (unwatch rules).
(clear)	<-- Removes all facts and rules from the CLIPS environment and cleans up agenda so that another program can be loaded.

3. List of files

Files contained in the distribution disks and a brief description of each of them are list below:

(Disk 1 - PASELS)

CLIPS.EXE <-- CLIPS environment

PREP.CLP <-- Pre-processor part of PASELS

PAVE.CLP <-- Post-processor part of PASELS

PAVE.KBS <-- Storage of info. obtained during preprocessing and will be used by post-processing

MODIN.DAT <-- Result of the pre-processor and input to the backcalculation program

SEARCH.OUT <-- Result of the backcalculation and input to the post-processor

USERS.DOC <-- The user's guide of PASELS, which you are reading

(Disk 2 - MODULUS)

MODULUS.BAT <-- Batch file of the MODULUS program

DATAGEN.EXE <-- Reads data from pre-processor and generates input for BISAR.EXE

BISAR.EXE <-- Generates BISAR deflection database for the given pavement structure

SEARCH.EXE <-- read deflection basin from FWD.DAT and search solution from the database, write result to "search.out"

FWD.DAT <-- example FWD data file

TMP.RES <-- example temporary data file

BIS.RES <-- example BISAR deflection database

APPENDIX I

INPUT GUIDE AND LISTING FOR FINITE ELEMENT PROGRAM TRANFLO FOR TRANSIENT SUCTION POTENTIAL CHANGES BENEATH PAVEMENTS

(See Note under Appendix B, p. 49)

APPENDIX J

DEFLECTION DATA FOR LOAD CORRECTION STUDY

(See Note under Appendix B, p. 49)

APPENDIX K

DECISION CRITERIA FOR NDT EQUIPMENT

INTRODUCTION

Decision criteria are the qualities or attributes that should be considered in selecting nondestructive testing equipment. It was found necessary to separate the criteria into two mutually exclusive categories: the characteristics of the device itself and the feasibility of its use at present. The two categories are further subdivided into attributes and decision criteria as will be seen in the following.

CATEGORY ONE: DEVICE CHARACTERISTICS

I. COST

A. Capital Cost -- Determination of capital costs shall include consideration of the following components:

1. Initial Cost -- The cost to purchase the equipment and accessories.
2. Salvage Value -- The expected salvage value of the NDT equipment and accessories at the end of its service life.
3. Equipment Life -- The expected life anticipated for the NDT equipment and its accessories.

B. Annual Data Collection Cost -- Determination of annual data collection cost shall include consideration of the following components:

1. Maintenance Cost -- Average annual maintenance costs over the life of the equipment, including both parts and labor.
2. Crew Costs -- The costs of the crew required to operate the equipment for one day of testing (an eight-hour day). Estimate labor costs using the following rates:

Driver	$ 6/hour
Technician	$10/hour
Engineer	$16/hour
Overhead	150 percent of salary and wages

3. Traffic Control Costs -- The estimated cost of controlling traffic for one day of testing, assuming that the testing is done during daylight hours over an eight-hour period on a four-lane highway.
4. Fuel/Oil Costs -- Fuel/oil costs to operate the equipment for an eight hour day.
5. Prime Mover Cost -- The cost per day for use of the towing vehicle, if required, not including fuel costs.

II. OPERATIONAL CHARACTERISTICS

A. Data Collection Speed -- The total time required to test a pavement station from the time the tow vehicle stops until it starts again after the measurement is completed. This time includes set-up, testing, data collection, and reloading.

B. Crew Training Requirements -- Personnel training includes actual time operating the equipment as well as reviewing the operations manual provided by the manufacturer. It should include familiarization with equipment operation, troubleshooting, data interpretation for verification, and calibration procedures. Requirements should be expressed as the total number of man-hours of training required for an entire crew.

C. Calibration Requirements -- The estimated number of hours of calibration required per week of use.

D. Traffic Delays -- This factor is a measure of the inconvenience to other road users. It is dependent upon the travel speed of the testing vehicle and upon the space occupied by the required equipment. It will be evaluated on a continuous scale from 0 to 1:

0 = No traffic delays.
0.5 = Complete obstruction of a single lane.
1 = Complete obstruction of two lanes.

E. Data Recording -- A measurement of the degree of automation and the ease of data acquisition, storage, and retrieval. It will be evaluated on a continuous scale from 0 to 1.

0 = No automation; all data must be hand recorded.
0.5 = Data is recorded automatically, but does not include test section or other relevant information.

0.8 = Data is recorded automatically and includes test section and other relevant information and can plot graphs of the load and deflection versus time data on an on board video screen.
1.0 = Data is recorded automatically including test section and other information has a graphical capability for displaying on an on board video screen the load and deflection versus time data immediately after it is measured.

F. Transportability -- A measurement of the degree of mobility of the equipment and the ease with which mass inventory deflection surveys may be undertaken. It will be evaluated on a continuous scale from 0 to 1.

0 = The equipment must be loaded and unloaded by hand; sensors must be attached to the pavement surface by gluing or by mechanical means to assure good coupling.
0.3 = The equipment is transported in a van and has some electrical, hydraulic, or mechanical assistance in deploying the loading device. Sensors must be attached to the pavement surface.
0.7 = The equipment is transported in a van and has some electrical, hydraulic, or mechanical assistance in deploying the loading device. Sensors may be placed and removed automatically,

and held in place by gravity.

1.0 = The equipment may be transported over distances by a towing vehicle, is mounted in its own specially equipped vehicle, and sensors may be placed and removed automatically and held in place by gravity.

III. DATA QUALITY

A. Repeatability/Precision -- The expected coefficient of variation of a measurement repeated at a single location.

B. Accuracy -- The expected error of the measured quantities. For deflection-type devices, this should incorporate the accuracy of both load measurements and deflection measurements.

C. Suitability -- Are the pavement responses measured the same as would occur when a 9-kip moving wheel load is applied? It will be evaluated on a continuous scale from 0 to 1:

0 = No.
0.4 = Procedure to convert to 9-kip moving wheel load requires use of assumed material properties of the layers.
0.7 = Accurate procedure available for conversion from the applied load to a 9-kip moving wheel load.
1 = Yes.

IV. VERSATILITY

For deflection-type devices:

A. Number of Deflection Sensors -- The actual number of deflection sensors used for each test.

B. Movability of Sensors -- Are the sensors movable, for the evaluation of load transfer, etc.? It will be evaluated on a continuous scale from 0 to 1:

0 = No.
0.5 = Yes. Requires sensors to be moved manually.
1 = Yes. Sensors can be moved automatically.

C. Range of Load Levels -- The range of load levels that the deflection measuring equipment can exert on the pavement. The rating will be on a continuous scale from 0 to 1 as follows:

0.0 = No load.
0.2 = One light load level.
0.4 = One heavy load level.
0.6 = A range of loads from light to medium.
0.8 = A range of loads from medium to heavy.
1.0 = A range of loads from light to medium.

The light loads shall be 0-4000 lbs.; medium loads, 4000-10,000 lbs.; and the heavy loads, 10,000-24,000 lbs. or more. For other NDT devices, versatility shall be evaluated as the number of types of measurements that can be made by a single device.

CATEGORY TWO: FEASIBILITY OF USE

I. RELIABILITY/MAINTENANCE DOWNTIME

The estimated time, in number of days per year, that the equipment will be out of service due to equipment failures, malfunctions, etc. This includes waiting time required to obtain necessary parts and service.

II. TIME IN SERVICE/DEGREE OF DEVELOPMENT

It will be evaluated on a continuous scale from 0 to 1:

0 = Equipment is in developmental stages and has not been field tested for pavement studies, and equipment or software is not yet developed for production testing.

0.5 = Equipment has been developed and field tested on a limited basis but is not in production or available commercially. Some software has been finalized.

1 = Equipment and software in fully developed use, accepted nationwide, available commercially, and is use for production testing.

DECISION WEIGHTS ON THE CRITERIA

Having decided what characteristics are important to consider in selecting nondestructive testing equipment, it is essential to determine the relative weights to put on each of the decision criteria.

Several types of weighting factors are possible. Weights can be multipliers in an additive system,

$$w_1 A + w_2 B + w_3 C$$

or weights can be exponents in a multiplicative system, as in

$$A^{w_1} B^{w_2} C^{w_3}$$

The attributes and criteria within Category One and within Category Two were combined using the additive method. However, the total utility was determined by combining the utilities of Category One and Two multiplicatively with exponential weights. This was done because if a device has either a very low Category One utility or a very low Category Two utility, its present use value is also low. The multiplicative scheme allows low values to have a more noticeable impact. However, it was desirable to keep Category One characteristics separate and obtain the utility for Category One additively in order to provide some indication of the devices' potential at current cost levels.

After the weighting system was decided upon, the weights had to be determined using expert opinions. The weights were determined using the method as illustrated in Figure K-1. This method has been shown to produce fairly repeatable results, probably due to the weight adjustment scheme. These weights were then normalized so that the weights in each division totalled one (1). The weights for each characteristic were then analyzed to determine the mean and standard deviation. Using this information, the final weights were determined in a group session. These final weights are given in Table K-1.

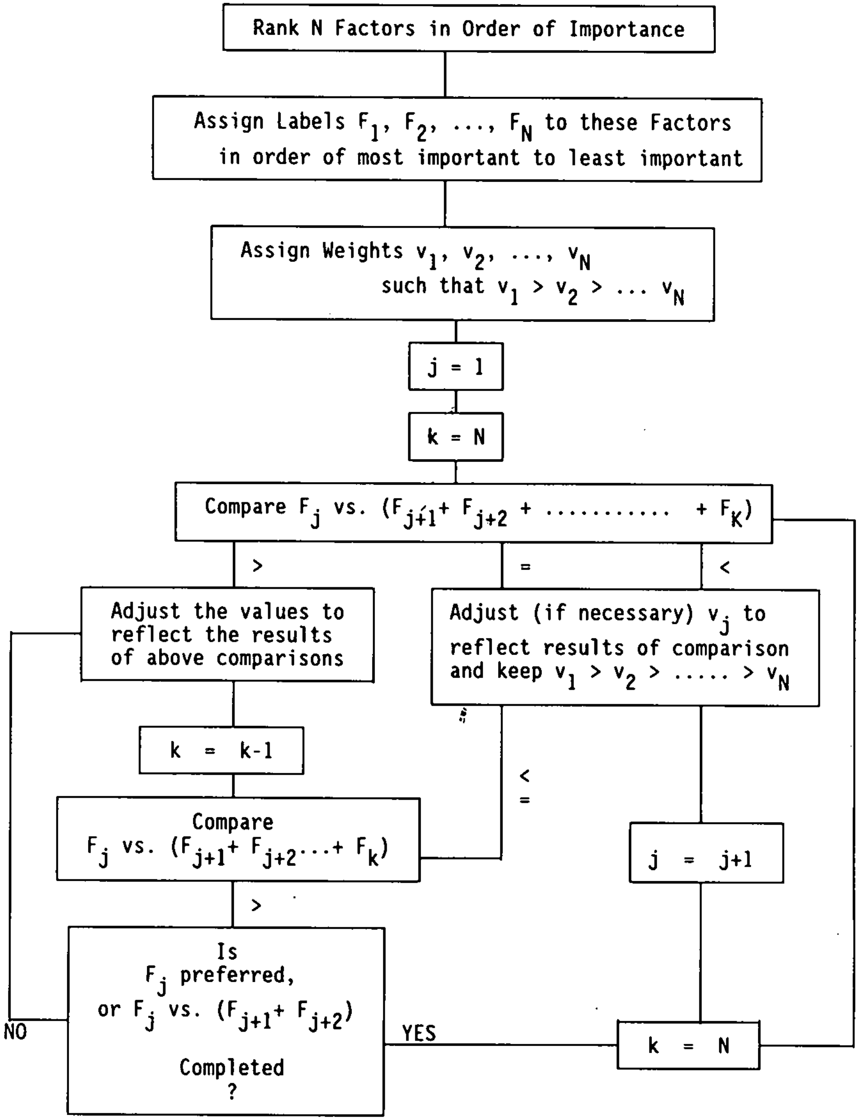


Figure K-1. Graphical Illustration of the Method Used to Determine the Weights of Each Attribute.

Table K-1. Determination of Weighting Factors

Note: The most important factor is each group should have a weight of 1. The remaining factors should have weights between 0 and 1 depending upon their relative importance. Refer to the flow chart in Figure K-1 for the proper technique for refining weights.

CATEGORIES

The utilities of Categories One and Two will be multiplied together in order to obtain the final utility value.

Category	Project-Level Relative Weight	Network-Level Relative Weight
One	1.0	1.0
Two	0.5	0.5

CATEGORY ONE ATTRIBUTES

The utilities of cost, operational characteristics, data quality, and versatility will be added together to obtain the utility of Category One.

Attribute	Project-Level Relative Weight	Network-Level Relative Weight
COST	.19	.23
OPERATIONAL CHARACTERISTICS	.22	.34
DATA QUALITY	.35	.28
VERSATILITY	.23	.15

CATEGORY TWO ATTRIBUTES

The utilities of Reliability and Time in Service will be added together to obtain the utility of Category Two.

Attribute	Project-Level Relative Weight	Network-Level Relative Weight
RELIABILITY	.48	.60
TIME IN SERVICE	.52	.40

COST DECISION CRITERIA

The utility of capital cost and annual cost will be added together to obtain utility of cost

Decision Criterion	Project-Level Relative Weight	Network-Level Relative Weight
Capital Cost	.52	.43
Annual Cost	.48	.57

OPERATIONAL CHARACTERISTICS DECISION CRITERIA

The utilities of data collection speed, crew training requirements, calibration requirements, traffic delays, data recordings, and transportability will be added together to obtain the utility of Operational Characteristics.

Decision Criterion	Project-Level Relative Weight	Network-Level Relative Weight
Data Collection Speed	.22	.23
Crew Training Requirements	.14	.10
Calibration Requirements	.15	.14
Traffic Delays	.20	.19
Data Recording	.19	.20
Transportability	.09	.13

DATA QUALITY DECISION CRITERIA

The utilities of repeatability/precision, accuracy and suitability will be added together to obtain the utility of Data Quality.

Decision Criterion	Project-Level Relative Weight	Network-Level Relative Weight
Repeatability	.28	.38
Accuracy	.41	.30
Suitability	.31	.32

VERSATILITY DECISION CRITERIA

For deflection-type devices, the utilities of the number of deflection sensors, movability of sensors, versatility of load plate location, and the number of load levels will be added together to obtain the utility of versatility.

Decision Criterion	Project-Level Relative Weight	Network-Level Relative Weight
Number of Deflection Sensors	.30	.43
Movability of Sensors	.30	.27
Range of Load Levels	.40	.30

For other NDT devices, the utility of Versatility will be obtained directly.

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. It evolved in 1974 from the Highway Research Board which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 270 committees, task forces, and panels composed of more than 3,300 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, the Association of American Railroads, the National Highway Traffic Safety Administration, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Frank Press is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research and recognizes the superior achievements of engineers. Dr. Robert M. White is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Samuel O. Thier is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purpose of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Frank Press and Dr. Robert M. White are chairman and vice chairman, respectively, of the National Research Council.

TRANSPORTATION RESEARCH BOARD
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

ADDRESS CORRECTION REQUESTED

000102H047
DIVISION ADMINISTRATOR

FEDERAL HIGHWAY ADMIN
3050 N LAKEHARBOR LANE #126