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16. Abstract
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A literature review was conducted to determine which of the programs worked best for other investigators and to select a small group for trial use in Louisiana. Deflection data was secured on a series of experimental sections constructed from pavement materials which had been previously tested. The programs chosen for the study included: BOUSDEF, EVERCALC, MODULUS and WESDEF. Two other programs, MODCOMP2 and ELSDEF, were initially included but technical difficulties necessitated their elimination from the study. Some of the programs had different control options, such as MODULUS and EVERCALC; therefore, a total of seven program options were included.

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Volume I contains the research report. Volume II contains the supporting data and MODULUS 4.0 User's Guide.

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Analysis and Evaluation of Methods for Backcalculation of M_R Values

Volume 1 - Research Report

Final Report

by

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ABSTRACT

Use of the 1986 AASHTO Design Guide requires accurate estimates of the resilient modulus of flexible pavement materials. Traditionally these properties have been determined from either laboratory testing or by backcalculation from deflection data. Since Louisiana has chosen the backcalculation approach, there was a need to review the available computer programs and determine which were most suitable for use in Louisiana.

A literature review was conducted to determine which of the programs worked best for other investigators and to select a small group for trial use in Louisiana. Deflection data was secured on a series of experimental sections constructed from pavement materials which had been previously tested. The programs chosen for the study included: BOUSDEF, EVERCALC, MODULUS and WESDEF. Two other programs, MODCOMP2 and ELSDEF, were initially included but technical difficulties necessitated their elimination from the study. Some of the programs had different control options, such as MODULUS and EVERCALC; therefore, a total of seven program options were included.

Statistical analyses were conducted using ANOVA techniques and the Student-Newman-Keuls, Duncan's Multiple Range and Least Significant Difference tests to determine whether the backcalculated and laboratory determined moduli were significantly different. Overall these tests showed that MODULUS step 3 and WESDEF provided the best match between estimated and laboratory measured moduli when all pavement layers were considered. The ability to run multiple deflection basins, automatic temperature corrections for hot mix asphalt moduli and internally developed estimates of layer moduli made MODULUS the choice of project investigators. Additionally, the selection of MODULUS by SHRP for use in the LTPP project ensures that any program improvements will be fully documented and made widely available to the technical community.

IMPLEMENTATION STATEMENT

The MODULUS 4.0 computer program has been selected as the most suitable one for use in Louisiana to estimate resilient moduli of pavement layers using falling weight deflectometer (FWD) deflection data. Estimates of pavement layer moduli backcalculated using MODULUS 4.0 step 3 will allow LDOTD personnel to develop the material property input data needed to design major overlays, rehabilitations and original designs for flexible pavements using the 1986 AASHTO Design Guides.

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INTRODUCTION

In 1986 the American Association of State Highway and Transportation Officials (AASHTO) published their Guide for the Design of Pavement Structures. Significant changes were made from the 1972 AASHTO interim guide. The design and procedures for new flexible highway pavements and for overlays of hot mix asphalt (HMA) were revised and expanded. The Louisiana Department of Transportation and Development (LaDOTD) immediately began to use the AASHTO Guide as the "building block" upon which to base new LaDOTD pavement and overlay designs for both rigid and flexible pavements.

One major change occurring in the 1986 AASHTO Guide was the use of resilient modulus (M_R) to characterize the materials used in flexible pavement design and rehabilitation. M_R became the definitive characteristic of pavement layer strength. The resilient modulus is a value that, theoretically, can be determined either from testing samples of material in the laboratory or from nondestructive deflection testing (NDT) on in-service pavements. Unfortunately, by 1986 the state-of-the-art for determining M_R from either method was still in the development stages. Researchers in highway and transportation departments, in consulting firms, and in universities began a concentrated effort to determine which laboratory and field techniques could provide consistent and dependable results for this critical pavement design parameter.

With the change to resilient modulus, the use of NDT with linear elastic layer theory for determining the M_R of pavement layers began to get more serious attention. Up to this point, linear elastic techniques had been widely used to calculate pavement stresses and strains using surface loads plus assumed layer strength characteristics, including modulus and Poisson's ratio, as program inputs. With wider use of NDT devices and the use of deflection data to estimate pavement layer M_R, many of the linear elastic computer programs, such as Chevron, Shell, and Bisar, became the "core" programs in backcalculation routines.

In general, the backcalculation programs require inputs of a surface load and deflection basin from an NDT device, along with pavement layer thicknesses and "seed" (initial estimate) moduli for each pavement layer. Using these inputs, a theoretical surface deflection basin for the given load and pavement inputs is calculated and then compared to the actual NDT deflection basin. If the differences meet certain tolerance limits, then the program stops, and the moduli are considered valid. If not the computer program adjusts the moduli, recalculates the surface deflection basin, and rechecks the basin tolerances. This iterative process continues until the required tolerances are met, and the final backcalculated moduli values are reported.

Several problems have occurred when using these newly developed programs. First, there is not a unique set, but multiple sets of layer moduli that can produce the same deflection basin. Secondly, the set of resulting layer moduli are extremely sensitive to the selection of the seed moduli. Thirdly, thin surface layers (HMA of less than 2 inches) created problems with convergence between the actual and theoretical surface deflection basins. Fourth, a rock or other very stiff layer within a 20' to 30' depth under the pavement affected the calculated deflections. Finally, there were no "correct" moduli to which the backcalculated moduli could be compared; there was only a reasonable range of moduli against which the backcalculated values could be compared.

Researchers have spent much of the last few years modifying these programs to correct observed deficiencies. They have also compared backcalculated moduli with laboratory moduli of recompacted samples and have compared the backcalculated moduli values obtained among the many routines available. Results have been mixed leaving many researchers puzzled as to what to try next. Much work is still required before these programs are reliable and before the results can be used without a critical analysis. Meanwhile, users must carefully evaluate these backcalculation programs to determine which gives the most reasonable results for their combination of soil, pavement, and NDT device.

LITERATURE REVIEW

Resilient modulus is a fundamental material property that is similar in concept to Young's modulus of elasticity since both are measured from stress-strain data. However, it differs from the modulus of elasticity in that it is determined from the unload portion of the load pulse in a repeated-load, triaxial compression test while Young's modulus is determined from the load portion of the test. Therefore, the resilient modulus is determined using the resilient (recoverable) portion of the axial strain (1). The resilient modulus (M_R) is defined by the ratio of the repeated axial deviator stress (σ_d) to the recoverable axial strain (ϵ_a) (2):

$$M_R = \frac{\sigma_d}{\epsilon_a} = \frac{\text{load/area of the specimen}}{\text{recoverable deformation/original height}} \qquad \text{(Eq. 1)}$$

With the recent emergence of the use of resilient modulus in pavement design, NDT methods have gained popularity as an economical technique for securing material property estimates. The Falling Weight Deflectometer (FWD) is gaining popularity because it can measure the whole deflection bowl while applying loads of the same magnitude as used in design (18 kip single axle loads).

There are two distinct parts to collection and use of NDT data: 1) the mechanical functioning and reliability of the instrument, and 2) the interpretation and utilization of the measured data (3). This report deals principally with the second, use of the FWD deflection data to backcalculate resilient modulus of pavement materials.

Backcalculation is defined as the process of estimating elastic stiffness properties of pavement materials by matching a measured deflection basin with a theoretical basin calculated from a computer program which receives as input the measured deflections produced by a test load plus other information about the pavement materials such as layer thickness, Poisson's ratio, and range of allowable modulus values (3). There are a whole host of backcalculation programs discussed in the literature. Several of the most common programs are briefly discussed in the following paragraphs.

BISDEF

BISDEF, a program developed by the U.S. Army Corps of Engineers, Waterways Experiment Station, uses a deflection basin from NDT results to predict the elastic moduli of up to four pavement layers. By matching the calculated deflection basin to the measured deflection basin. The program uses an iterative process that provides the best fit between measured deflection and computed deflection basins (4).

The basic assumption of this method is that dynamic deflections correspond to those predicted from the layered elastic theory. This method uses the BISAR layered elastic program to compute the deflections, stresses, and strains of the structures under investigation (4). BISAR has a unique capability of varying the bond between layers in the pavement, i.e. variable slip between layers. However, this capability makes the program run time quite long. Additionally BISAR is also a proprietary program and can only be used by licensees.

To determine the layer moduli, the basic inputs include initial estimates of the elastic layer pavement characteristics, as well as the measured deflection basin. Inputs for each layer include:

a) Thickness of each layer,

b) Range of allowable modulus,

c) Initial estimate of modulus (seed modulus), and

d) Poisson's ratio (4).

BOUSDEF

BOUSDEF is a backcalculation program created at Oregon State University to determine in-situ pavement layer moduli using deflection data through backcalculation technique. The program was developed for use with conventional flexible pavements built on a fine grained subgrade which included a coarse grained aggregate base/subbase. The analysis methodology is based on the method of equivalent thicknesses and Boussinesq theory. BOUSDEF utilizes the seed modulus and layer thickness to determine the equivalent thickness of the pavement structure. Deflections for the given NDT load and load radius are then calculated. The calculated deflections are compared to measured deflections. If the sum of the differences is greater than the tolerance specified by the user, the program will begin iterating in an attempt to produce convergence between the calculated and measured deflections by changing the moduli before computing a new set of deflections. This iteration process continues until the sum of the deflection differences is less than the tolerance or until the maximum number of iterations has occurred. The backcalculated moduli may be used to evaluate the existing pavement structural strength and/or for use in mechanistic overlay design procedures (5).

BOUSDEF can be operated on any IBM or compatible microcomputer with a DOS version 3.1 or higher. BOUSDEF is an integrated program which includes the capability for creating, editing, and analyzing a data file (5).

CHEVDEF

CHEVDEF is similar to BISDEF except it uses CHEVRON n-layer computer program in the forward calculation scheme. CHEVDEF uses the sum of the squares of the absolute error as the convergence criterion rather than the sum of the differences as in BISDEF. This program can backcalculate reasonable modulus values for conventional flexible pavement sections, i.e., pavement sections having a layer arrangement that has decreasing stiffness with depth. However, it gives poor results for pavements having thin HMA layers or pavements with intermediate soft or hard layers such as cement stabilized bases or subbases (6 and 7).

COMDEF

COMDEF is an interactive, user-friendly, public domain FORTRAN program which backcalculates layer moduli for composite pavements based on deflections measured by a FWD. COMDEF is based on a new method which uses a matrix of precalculated solutions stored in 33 standard data base files. The method used in COMDEF is completely automated and numerically approximates the theoretical deflection basin which would be calculated by layered elastic theory. The data compression technique and interpolation routines used by COMDEF allow deflections to be calculated almost instantaneously from a relatively small data base with a high degree of accuracy. The COMDEF data base was developed for composite pavements which include portland cement concrete layers with moduli in excess of 3 million psi. As such it is not applicable to pavements included in this study (8).

ELMOD

ELMOD is a microcomputer program based on the method of equivalent thicknesses, originally developed by Odemark. This is a process where by a layered pavement structure is transformed into an equivalent Boussinesq system above the subgrade using the same process as described for BOUSDEF. ELMOD used the layer transformation approximation rather than one of numerical integration. The advantage of this approach is that nonlinear materials may be considered and the computational process is much faster than "conventional" layered elastic analysis backcalculation computer codes (9 and 10).

The basic ELMOD inputs include layer thickness and pavement surface deflections (a total of seven). The program can analyze up to a 4-layer pavement structure; it automatically calculates the subgrade nonlinear-stress relationship for each FWD drop, and it can be used to evaluate other significant factors such as remaining life and required overlay thickness (10).

The program computes moduli by using the outer deflections to first estimate the subgrade modulus. The moduli of the HMA and base courses are determined by an iterative process which uses the center deflection and the shape of the deflection basin. The subgrade modulus at the center of the loading plate is adjusted for stress level, and the outer deflections are checked. At this point a new iteration is made if needed. The program generally takes less than five seconds to run (10).

ELSDEF

ELSDEF is similar to BISDEF, except that ELSYM5 is the elastic layer program rather than BISAR. An iterative procedure is also used to determine the best fit between measured and computed deflections. The modulus adjustment procedure involves determining a relationship between log modulus and calculated deflection for each unknown modulus by varying the assumed moduli and calculating the deflections. This relationship is then used in the iteration process to find a set of moduli that produce minimum errors. Program input are similar to others using this approach, i.e., load, deflection basin data, error tolerance, layer thickness, Poisson's ratio, seed moduli, and allowable range of moduli (10).

The number of layers with unknown moduli cannot exceed the number of measured deflections. No provision is available for nonlinear material behavior, and limitations to the approach are related to this fact. The program can be run with or without a rigid base. The procedure is sensitive to the choice of seed moduli (10).

EVERCALC

EVERCALC is a mechanistic-based pavement analysis computer program that includes the Chevron N elastic layer program. This microcomputer program uses an iterative procedure of matching the measured surface deflections with the theoretical surface deflections calculated from assumed elastic moduli. The program has converged on a solution when the summation of the absolute values of the differences between the measured and calculated surface deflections falls within a preset allowable tolerance (generally 10 percent or less for a deflection basin described by five deflections). Lower tolerance levels will produce more accurate solutions; however, the 10 percent tolerance results in modest computer run time of five minutes for a three-layer pavement (10).

The program develops estimates of initial "seed" moduli internally and backcalculates the modulus for each pavement layer. The seed moduli are estimated using internal equations, developed from regression relationships between pavement layer moduli, load, and various deflection basin parameters (10).

ISSEM4

ISSEM4 is a mechanistic-based pavement analysis computer program based on the ELSYM5 program. As in most programs, it uses an iterative procedure of matching the measured surface deflections with the surface deflections calculated from ELSYM5 using assumed elastic moduli. The program uses five deflection points in the backcalculation process for three-layer structures; however, these points are from a fitted curve of the actual deflection measurements. A typical three-layer run takes about 5 minutes on a PC (10).

LOADRATE

The LOADRATE program uses a series of regression equations between load and deflection based on results generated using ILLI-PAVE. The program was developed specifically for use with surface-treated pavements typical of secondary roads. Regression equations were developed to relate the nonlinear elastic parameters of the bulk stress model (for the base material) and the deviator stress model (for the subgrade material) with the deflections at the load point and at some distance away from the load (6). Since the principal roadway surface type of interest in this present study is HMA, and LOADRATE was developed for surface treatments, it was not given any further consideration.

MODCOMP2

The MODCOMP2 program utilizes the Chevron elastic layer computer program for determining the stresses, strains and deformations in the pavement system. Since there is no closed-form solution for determining layer moduli from surface deflection data, an iterative approach is used that requires an input of seed moduli for each layer. The basic iterative process is repeated for each layer until the agreement between the calculated and measured deflection is within the specified tolerance or until the maximum number of iterations has been reached (4 and 10).

The program capabilities include the following:

1) Up to eight layers can be included in the pavement system.
2) The layer combinations may be linear elastic or nonlinear stress dependent.
3) The program is capable of accepting data from several typical NDT devices (e.g., FWD, Road Rater, and Dynaflect).
4) It is capable of accepting up to six load levels.

The input data required by the program are:

1) Surface deflection and radial distances of geophones from the center of the load,

2) Applied load,

3) Poisson ratio,

4) Base and subgrade soil type, and

5) Seed modulus for the pavement layers.

The computed deflections are compared with measured deflection, and the ratio of adjustment of layer is based on the magnitude of the difference in calculated deflections. This process is repeated until the difference between the computed and measured deflection is within the specific tolerance (4 and 11).

MODULUS

MODULUS is a backcalculation program that generates a data base of modulus deflections using WES5, a linear-elastic program created by the U.S. Army Corps of Engineers Waterways Experiment Station in Vicksburg, Mississippi. This program uses the Hooke-Jeeves' pattern search algorithm 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 before the deflection matching process begin. 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 estimate the calculated deflection basin and the corresponding layer moduli (6 and 7).

Using an IBM-AT 286 with an 8086 math co-processor chip, approximately 30 minutes is required for MODULUS to calculate and develop the data base for a four-layer pavement section; however, once the data base is computed, only one to two minutes is required to backcalculate moduli for each deflection bowl. The data base, moreover, can be saved and used repeatedly on similar pavements for analysis of other deflection data. Because of the short turn-around time to backcalculate moduli, it is now practical to perform the backcalculation analysis in the field in order to check the reasonableness of data before moving away from the test site. The program has the capability to handle both linear and nonlinear material behavior (7 and 12).

OAF

The OAF program was developed to utilize the deflection data from the FWD. The procedure requires measurement of deflections at 0, 30, 60, and 100 cm from the applied load. Backcalculation of layer moduli for a specific site requires inputting the following information into a OAF which uses the ELSYM program to calculate surface deflections:

1. Surface deflection measurements and load configurations
2. Base type
3. Layer thickness
4. Poisson's ratio for all layers, and
5. HMA modulus at field pavement test temperature (11)

Essentially, the program solves for the moduli of the various layers by attaining compatibility between measured and computed deflections (11).

SEARCH

SEARCH was developed at the Texas Transportation Institute, and uses a pattern-search technique to fit deflection basins with curves shaped like elliptic integral functions which represent solutions to the differential equations used in elastic layer theory. To account for multiple layers, a generalized form of Odemark's assumption is used to transform the thickness of all layers to an equivalent thickness of a material having a single modulus. The input data include:

1. Thickness of HMA and granular base layers
2. Force applied and radius of loading plate, and
3. Measured deflection values, and their radial distances, from center of loading plate (4)

The program searches for a set of elastic moduli that fit the measured basin to the calculated basin with the least average error. The output includes calculated moduli, computed and measured deflections, force applied, and squared error of the fitted basin (4).

WESDEF

The WESDEF computer program also utilizes WES5. WESDEF, was developed by the U.S. Army Corps of Engineers, Waterways Experiment Station. The program can calculate modulus values for one set of deflections and multiple loads. The deflection data can be entered manually by utilizing the INDEF program which accompanies the WESDEF program.

The basic assumption of WESDEF is that dynamic deflections correspond to those predicted from the same loads using static layered elastic theory. This program uses the WES5 layered elastic program to compute the deflections for the structure under investigation. The program compares computed and measured deflections and compares the differences to a 10 percent tolerance range, if not within tolerance, the program varies the layer moduli, recompute deflections and compare to measured deflections in an attempt to converge to the 10 percent tolerance range. If after three iterations the tolerance range is still greater than 10 percent, the iteration process will terminate (13).

VESYS

The VESYS program was used to develop a graphical procedure for backcalculating the pavement parameters. The VESYS model incorporates the viscoelastic and fatigue properties of the pavement materials. For the analysis of existing pavement systems, algorithms were developed that can be used with measured load deflection data and known material thickness or properties. The algorithms were developed by applying statistical regression analysis techniques to the VESYS-generated response data (11). Since the inputs required for the VESYS model are very complicated and determining the compatibilities between the properties used by the researchers and those of Louisiana materials was not possible, VESYS was determined not to be a candidate for use in this project.

COMPARISONS OF PROGRAMS

Ali and Khosla ran four different programs (ELMOD, VESYS, MODCOMP2, AND OAF) on the same sample data and compared the results to each other and to laboratory test results of pavement materials. Their findings showed both ELMOD and VESYS had great potential for pavement analysis. VESYS had the least variation between predicted and laboratory moduli values with the ratio $M_{R(lab)}/M_{R(pred)}$ ranging between 0.48 and 1.08 with most values between 0.77 and 0.97. The ratio values for ELMOD varied between 0.54 and 1.56, with most values between 0.80 and 1.26. Both MODCOMP2 and OAF predicted moduli which showed large variations from the laboratory values (11).

Lee, Mahoney, and Jackson examined the program EVERCALC and verified it in two different ways. The first verification approach was to compare theoretical and backcalculated moduli for a range of three-layer pavement systems. This was accomplished by using the Chevron N-layer elastic analysis program to generate deflection basins for specified layer moduli and thickness conditions. These comparisons showed modest differences (about 8 percent for HMA, 6 percent for the base course, and less than 2 percent for the subgrade). The largest differences for HMA were observed for thin surfaces with low stiffness. As the HMA layer thickness increased, both the base and subgrade moduli differences increased. The second verification approach was to compare backcalculated and laboratory moduli based on FWD tests and field material sampling along with appropriate laboratory testing. The results show the greatest range of differences for the HMA layers (438 percent to 1 percent difference) followed by the base (60 percent to 0 percent) and subgrade materials (59 percent to 2 percent) (14).

Alexander, White, and Barker reported that WESDEF compared favorably (almost identical) to BISDEF for typical values for AC, PCC, and composite pavements using FWD deflection data. WESDEF matched the deflection basin about 4.5 times faster than BISDEF (13).

Tam and Brown reported that the ELMOD program can only analyze two- and three-layered structures, although a source from Dynatest has indicated that it can analyze structures with up to four layers (9).

Mahoney, Coetzee, Stubstad and Lee compared ELMOD, ELSDEF, EVERCALC, ISSEM4, and MODCOMP2 with each other and laboratory results. It is reported that the five programs showed relatively similar results but all showed greater difference compared to the laboratory results (10).

OBJECTIVES OF RESEARCH

A. Select an appropriate backcalculation procedure for estimating pavement layer resilient modulus from FWD deflection measurements.

B. Compare FWD estimated resilient modulus values with those determined from laboratory tests.

C. Develop a preliminary procedure for estimating the resilient modulus of pavement layers using deflection measurements.

SCOPE

Because of the limited time and funds available for this study, no laboratory testing of pavement materials was possible. Therefore, the evaluation of candidate programs was made using deflection data taken on a series of experimental projects built on US 71-167 in 1975-76 for which extensive material test data was available (15 and 16). Additionally, the initial selection of computer programs was made on the basis of comparisons and evaluations included in the technical literature.

To verify the use of the backcalculation approved to other pavement materials, additional field data should be collected as well as laboratory moduli determination for those pavement materials. Comparisons between moduli predicted from backcalculation procedures and moduli measured in the laboratory will indicate their applicability to other materials.

METHODOLOGY

In this study the process for selecting a computer program for backcalculation of pavement layer moduli involved several steps. First a literature survey was conducted to identify the computer programs which have shown the best promise for calculating reasonable estimates of pavement moduli. Once the programs were identified, the results from comparative studies which used more than one program were reviewed in order to develop a smaller set of candidate programs which appeared to work best, which required the minimum amount of prior information about the pavement materials, and which could be used by operators with limited experience. Based on these factors, a set of six computer programs was selected for use in this study.

After selecting the programs, a series of deflection measurements were taken by the LTRC research staff on each of the experimental base sites on US 71-167 south of Alexandria. Five deflection tests for each of four different loads were performed on each of the 18 control and test sections. These deflection data along with pavement layer data were input into each computer program and the layer moduli estimated. The average moduli were calculated two different ways: 1) calculating moduli of each layer from individual deflection basins and averaging the resulting moduli for each layer and 2) averaging all deflection basin readings for a given load and computing the moduli from this averaged basin and loading. The estimated moduli were compared to moduli determined from laboratory tests conducted as part of the experimental base project (15 and 16).

Statistical comparisons were made using analysis of variance (ANOVA) techniques and the Student-Newman-Keuls, Duncan Multiple Range, and Least Significant Difference tests. Detailed studies of the results from the 18,000 pound axle load led the authors to conclude that two programs, MODULUS and WESDEF, provided the best match-up between predicted and measured moduli.

Other factors considered in making a program selection included:

1) Seed moduli and range of moduli input requirements,
2) Adjustments for temperature effects on moduli of the HMA materials,
3) Efficiency of operations when large deflection data sets were being processed,
4) Ease of use of the program,
5) Ease of keeping the program up to date, and
6) Documentation available on the program.

Based on the above factors, MODULUS 4.0 step 3 was selected as the most appropriate for use in Louisiana. Additionally a preliminary procedure for collecting NDT data was prepared as a part of the effort. The principal objective of the field data collection effort was to provide pavement layer moduli input for use in overlay rehabilitation, and original design according to the 1986 AASHTO Design Guide.

ANALYSIS OF RESULTS

BACKCALCULATION PROGRAMS SELECTED FOR THIS STUDY

The original research plan included securing as many of the programs as possible and then using a common set of field deflection data to determine which programs performed best in backcalculating pavement layer moduli. Project staff encountered considerable difficulty both in securing copies of the computer programs and getting them to work on the project computer. Additionally the LTRC staff experienced unavoidable delays in taking delivery of the FWD and tow vehicle. As a result project staff were unable to secure deflection data in enough time to evaluate a large group of the computer programs. Therefore, the selection of candidate programs was made using results from the technical literature described in the previous sections.

Project staff initially selected six computer programs for use in the balance of the study:

1. BOUSDEF
2. ELSDEF
3. EVERCALC
4. MODCOMP2
5. MODULUS
6. WESDEF

These programs appeared to be representative of those discussed in the literature and typically used in comparisons studied. Additionally, most of the programs have been developed for and adopted for use by agencies involved in routine NDT evaluations.

The developers of each of these programs were contacted and copies were received for all but MODCOMP2. However, the project staff was unable to get ELSDEF to work on the available PC and, after considerable effort, eliminated it from the study. Several telephone calls were made to determine the status of MODCOMP2 but because of some variations in surface deflections in the vicinity of the load experienced with the CHEVRON elastic layer program, MODCOMP2 was withheld from project staff until the problems were solved. Consequently, the programs listed in Table 1 represent the four candidate backcalculation programs utilized in the balance of the project. All programs are in the public domain.

BOUSDEF is a new program based on the method of equivalent thicknesses which has not been widely tested and it is reported to have short run times. A new version of EVERCALC (EVERCALC 3.3) was just distributed in February 1992. MODULUS 4.0 was chosen because it has fared very well in comparisons both in the literature and by reputation among the pavement modulus research community. WESDEF was readily obtained from the Corp of Engineers and has been used extensively in their pavement evaluation work, and fared well when predicted moduli were compared with laboratory determined moduli.

Table 1.

Backcalculation Computer Programs

Program Name	Layered Elastic Program	Number of Layers	Stiff Layer	Creator	Ref.
BOUSDEF	Method of Equivalent Thicknesses	5	NO	(for) Oregon DOT	5
EVERCALC 3.3	CHEVNL	5	YES	(for) Washington State DOT	17
MODULUS 4.0	WES5	4	YES	Texas Transportation Institute	18
WESDEF	WES5	5	YES	U.S. Army Corps of Engineers	19

DESCRIPTION OF TEST SITE AND LABORATORY DATA

This project utilized a series of test sections located in central Louisiana, between the communities of Meeker and Chambers in Rapides Parish as shown in Figure 1. The test sections are located on a portion of US 71-167 which accommodates a moderate volume of mixed vehicular traffic. The terrain at the site is generally flat with poor drainage and the subgrade material is a relatively uniform, fine-grained soil. The average daily air temperature at the test site ranged from 39°F to 84°F and the annual rainfall ranges from 55 to 60 inches (15).

The test site contained eighteen sections; fourteen test sections and four control sections arranged as shown in Figure 2. The control sections were used as control sections in the previous study by Hadley (15); however, in this research study the control sections were treated the same as the test sections. Included in the cross sections are three different base types (black base, soil cement, and cement stabilized sand-clay-gravel) of several thicknesses, and two hot mix asphalt (HMA) surface thicknesses. Each section is approximately 550 feet long with a 50 feet transition zone between adjacent sections. Construction of the test sections began in 1975 and was completed 1976 (15). All sections were recently overlaid with a 3-inch layer of HMA.

The properties of each test section material were measured in the laboratory as part of a previous LTRC research project and reported by Hadley (15). The average of the laboratory values were determined in order to compare the computer backcalculated values obtained from each computer program to the

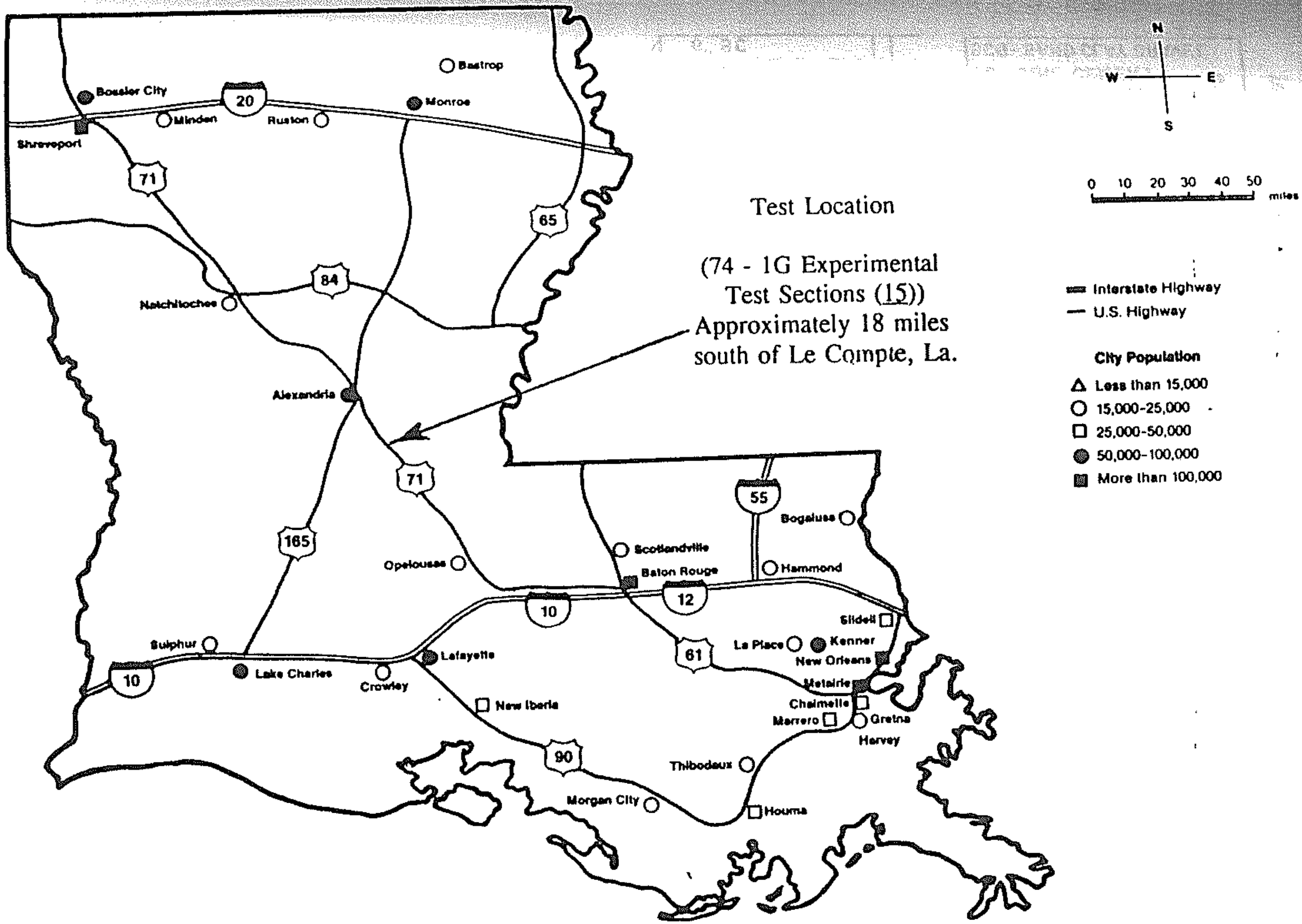

Figure 1. Location of experimental base test sections

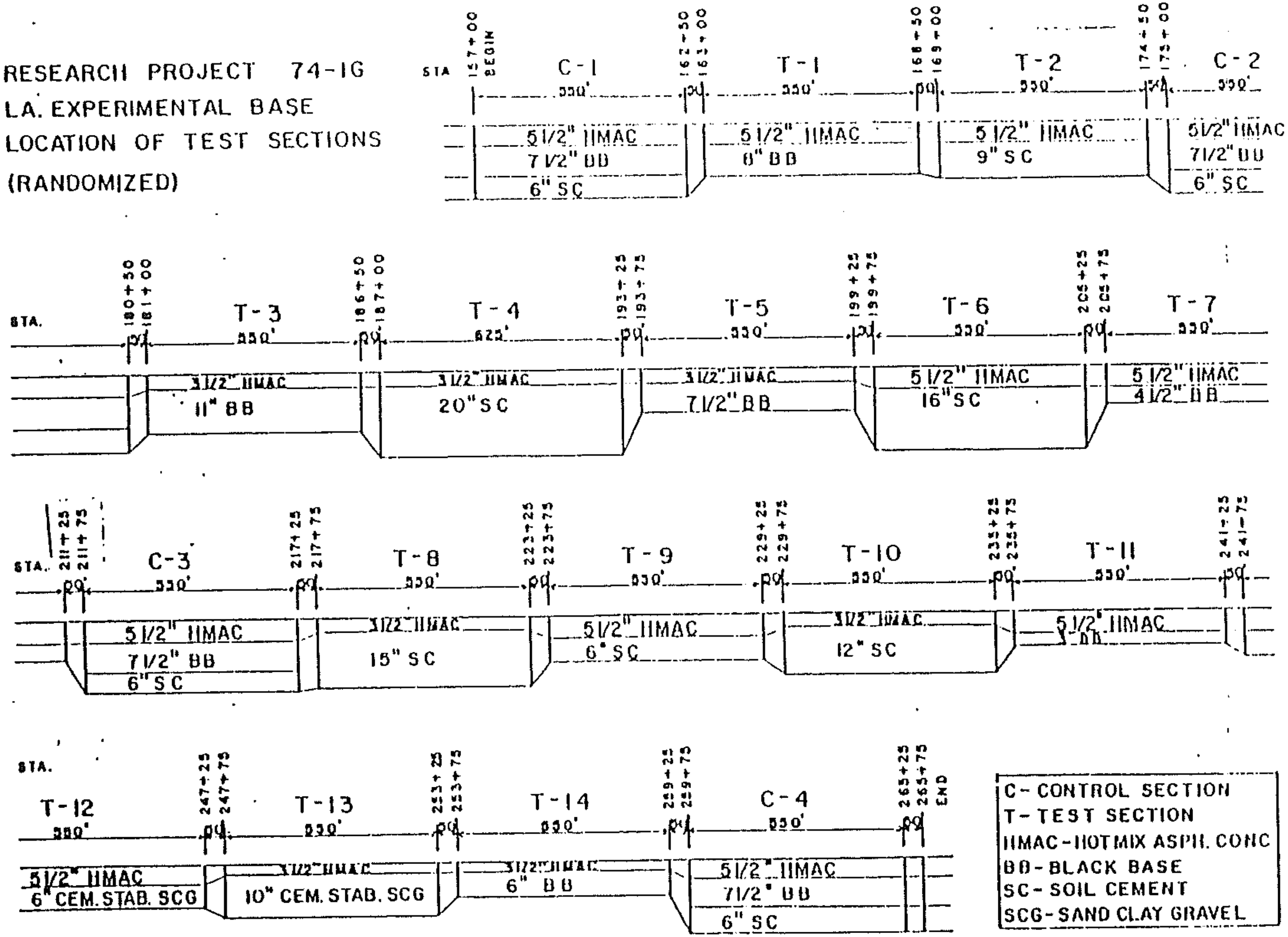

Figure 2. Experimental base pavement cross sections in the laboratory.

laboratory determined values, in order to assess the ability of each program to estimate the measured moduli.

The average layered modulus (in psi) values from Hadley (15) are given in Table 2. Hadley determined the properties of the surface and base materials using the indirect tensile test. Values used in this report were determined by first calculating the mean and standard deviation of all the data; next the outliers were removed using a 5 percent significance level; the mean was recalculated using the remaining data. Properties of the subgrade soil were determined using a tri-axial resilient modulus test. Values used in this report were determined in the manner described for surface and base materials. The individual test values were extracted from Tables 46-50, 52, and 56 of reference 15. The resilient modulus values from field cores taken from each of the materials are summarized in Volume 2-Appendix 1.

Poisson's ratio for the materials is shown in Table 3. These values were determined from laboratory tests on field cores secured after construction using the material described in reference 15.

FEATURES TO BE CONSIDERED DURING THE SELECTION PROCESS

When selecting a backcalculation program several features should be considered. To begin with, it is important to determine how extensively the program has been used in past research studies and, if possible, how well the backcalculated moduli from a program compare with moduli values determined.

Table 2.

Average Laboratory Modulus Values for Layers 2, 3, and 4 As Secured From Hadley (15)

Section	Layer 1[a]	Layer 2	Layer 3	Layer 4
C-1[b]	500000	540000	371400	6175
C-2	500000	540000	449100	6384
C-3	500000	540000	477500	8769
C-4	500000	540000	378600	13074
T-1[c]	500000	563000	494500	6546
T-2	500000	563000	449400	7229
T-3	500000	563000	494500	11367
T-4	500000	563000	594000	12851
T-5	500000	563000	494500	11282
T-6	500000	563000	560900	8397
T-7	500000	563000	494500	7479
T-8	500000	563000	616000	9620
T-9	500000	563000	408300	13415
T-10	500000	563000	564000	14710
T-11	500000	563000	494500	12812
T-12	500000	563000	500000	11266
T-13	500000	563000	500000	11827
T-14	500000	563000	494500	14257

[a]The modulus values for layer 1 (overlay) were not determined in the laboratory, but were assumed to be reasonable values.
[b]C-1 indicates control section 1 as shown in Figure 2.
[c]T-1 indicates test section 1 as shown in Figure 2.

Table 3.
Poisson's Ratio for Each Material As Determined From Test On Field Cores (16)

Material	Poisson's Ratio
HMA	0.35
Soil Cement	0.18
Sand Clay Gravel	0.10
Subgrade	0.49

It is also desirable to determine how often the program predicts moduli that are out of a reasonable range for the material being evaluated.

Finally, the program requirements, ease of use of the program, and the required technical expertise of the operator are important also. Included in this last group of factors is the basic mathematical theory used in the program, type and size of computer required, length of run time for the program to generate output, availability and ease of understanding the user's guide, and availability of help from the developers of the program.

DETERMINATION OF SEED MODULI

The range of typical modulus values expected for various pavement materials has to be determined and input for some of the computer programs. These initial estimates of moduli are called the seed moduli. Range of the seed moduli for the pavement layers were estimated in the following manner. The range of test results for the HMA material tested by Hadley (16) was from 100,000 psi to 1,200,000 psi for a standard reference temperature of 77°F. Since the FWD data were performed at temperatures other than 77°F, the HMA seed moduli had to be corrected for temperature. The temperature correction was secured from a semi-log plot of "stiffness correction factor" vs temperature shown in Figure 3 (18). The seed modulus for a particular test was estimated by multiplying the correction factor derived from Figure 3 by the range of moduli secured from Hadley's laboratory data.

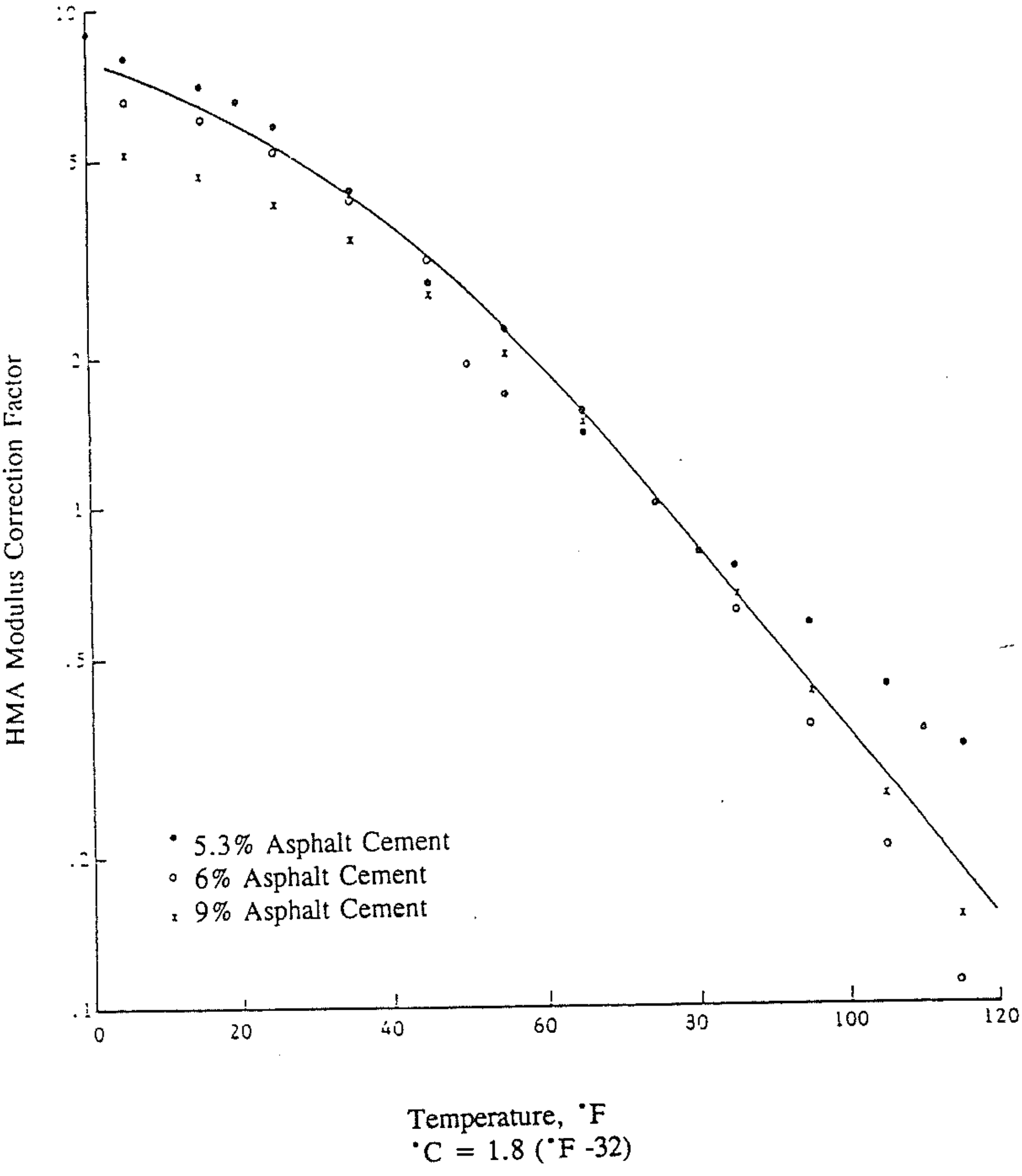

Figure 3. Relationship selected for modifying HMA modulus as a function of temperature

The range of moduli for the cement stabilized layers was estimated to be from 100,000 psi to 1,000,000 psi with Hadley's mean laboratory value used as the seed modulus. The range of moduli for the subgrade was estimated to be from 1,000 psi to 25,000 psi, with the seed modulus being the mean laboratory value. Volume 2 -- Appendix 2 contains a procedure for estimating seed moduli for various layers that was secured from reference 19 and 20. This procedure can be used for pavements where the pavement properties are unknown. The procedure was checked for the experimental test sections and appears to work well, except for cement stabilized bases, where the estimated values were found to be too small when compared to Hadley's laboratory results for the cement stabilized materials.

PROGRAM OPERATION TO ESTIMATE M_R

Each of the four computer programs required the same types of input data and each creates an output file of backcalculated moduli. A brief description of the operation of each program is included in the following paragraphs. The program and option designations used in this portion of the project are defined below:

Program

1	=	MODULUS step 2.
2	=	MODULUS step 3.
3	=	EVERCALC with no rigid layer.
4	=	EVERCALC with rigid layer.
5	=	EVERCALC with rigid layer and high water table.
6	=	WESDEF
7	=	BOUSDEF

Program 1, MODULUS step 2, is designed for a user who is familiar with material information but who has limited experience with modulus backcalculation techniques. For this option the user selects the material types, thicknesses for the pavement layers, and pavement temperature at time of testing, and the program assigns the range of acceptable moduli and Poisson's ratio values to be used in the analysis. MODULUS is a menu driven program. To begin the program, the following inputs for the data input option of the program are required:

- file name,
- highway and location,
- station number where the tests were performed,
- number of deflection bowls included in the data set,
- load applied to pavement,
- lane tests were performed in, and
- deflection reading for each sensor.

Once the input file has been generated and saved, the backcalculation step in the program can be run. This step requires that the input file name and the data set be defined by indicating beginning and ending stations, then it is necessary to select Step 2) "input material types." Now the program requires:

- load plate radius,
- number of sensors and their distance from the center of the plate,
- surface thickness,
- aggregate type,
- average or range of values for the HMA modulus adjusted for temperature at time of test,
- HMA temperature at time of deflection testing, the program automatically adjusts the moduli to standard temperature of 77°F,
- base and subbase type and thickness, and
- subgrade type.

Now the program backcalculates the modulus value for each layer of the pavement. Once the program has completed the backcalculation process, the output is stored and can be printed. The run time for this program is approximately two minutes on a 386, 40 megahertz IBM PC or compatible computer.

Program 2, MODULUS step 3, is designed for the more knowledgeable user. Program 2 has the same input option as program 1. After the input has been entered and saved, the backcalculation option can be executed. As for program 1, the operator must enter the input file name and define the data set with beginning and ending station, then it is necessary to select Step 3) "Run a Full Analysis." In this option the user supplies all of the input parameters needed to perform the analysis. The user has full control over all of the inputs used in the analysis. This is in contrast to MODULUS step 2 where the computer program assigns layer moduli and Poisson's ratios using typical values for similar materials as defined by staff at TTI. For step 3 the program requires the following input:

- load plate radius,
- number of sensors and their distance from the center of the plate,
- thickness of each pavement layer,
- range of moduli values for each pavement layer,
- Poisson's ratio for each pavement layer, and
- seed modulus and Poisson's ratio for the subgrade.

Now the program backcalculates the modulus value for each layer in the pavement structure and stores the output which can be printed. MODULUS step 3 takes approximately 2.5 minutes on a 386, 40 megahertz IBM PC or a compatible computer.

Program 3 is EVERCALC without a rigid layer and is also menu driven. To begin option 1) "Edit General Data File" must be selected to begin preparing the input file:

- file name,
- number of layers,
- units (english or metric),
- load plate radius,
- number of sensors and their distance from the center of the load plate,
- temperature correction option,
- method of temperature measurement (direct or Southgate method),
- method of estimating seed moduli (internal equations or engineering judgment),
- stiff layer option,
- maximum number of iterations before terminating the run,
- deflection tolerance in percent, and
- modulus tolerance in percent.

For this option of EVERCALC, "no" was selected for the stiff layer option. Program developers suggest that the maximum number of iterations be set at 3, 5, or 10 (all are considered acceptable) and that the deflection tolerance range from 1 to 10 percent. After the general data file has been generated and saved, step 2) "Enter Deflection Data Interactively" is selected for each pavement cross section. In this step the following input is required:

- file name for each layer,
- Poisson's ratio for each layer at standard temperature of 77°F,
- seed modulus for each layer at standard temperature of 77°F,
- modulus range,
- station number where test was performed,
- thickness for each layer,
- number of deflection data sets,
- temperature of the pavement at the test site, the program automatically adjusts moduli to standard conditions,
- load applied to pavement, and
- deflection at each sensor.

Once this file is saved, the program goes back to the main menu and step 3) "Perform Backcalculation" can be selected. In this step, the program backcalculates the modulus for each layer and saves it in an output file. The run time for the EVERCALC program is approximately 1.5 minutes on a 386, 40 megahertz IBM PC or compatible computer.

Program 4, EVERCALC run with a rigid layer, is run just like program 3 except in the general data file the stiff layer option is indicated by a "yes" and in step 2 the stiff layer modulus value and Poisson's ratio must be input. The developers recommend that the stiff layer modulus value be 10 times the modulus value for the subgrade (17). This version of EVERCALC also takes approximately 1.5 minutes on a 386, 40 megahertz IBM PC or compatible computer.

Program 5, EVERCALC run with a rigid layer and a high water table, is run just like program 4 except that the developers suggest that the stiff layer modulus value be reduced to 2 or 3 times the modulus value for the subgrade (21). This version of EVERCALC also takes approximately 1.5 minutes on a 386, 40 megahertz IBM PC or compatible computer.

Program 6, WESDEF, is not menu driven. Data is input through a program called INDEF with the following input required:

- file name,
- number of sensors and their distance from the center of the load plate,
- deflection for each sensor,
- number of loads per deflection bowl,
- load applied to the pavement,
- load plate radius,
- number of pavement layers,
- layer type,
- seed moduli and range for each layer,
- layer thickness, and
- slip condition (adhesion between the layers, ranges from full adhesion to full slip).

After the input information is entered and stored, the INDEF program can be exited and the WESDEF program can be executed. After identifying an output file name, the WESDEF program can compute the backcalculated modulus values. The WESDEF program takes approximately 0.5 minutes on a 386, 40 megahertz IBM PC or compatible computer. However, only one deflection basin at a time can be input into the program. For a second deflection basin, INDEF must be called, the input entered for the second basin and then WESDEF is run. To evaluate an extensive set of deflection data is a tedious job using the WESDEF program.

Program 7, BOUSDEF, is menu driven and requires the following input:

- input file name,
- number of layers,
- thickness of each layer,
- Poisson's ratio of each layer,
- seed moduli and range for each layer,
- density of each layer,
- load plate radius,
- number of sensors and their distance from the center of the load plate,
- load applied to pavement,
- deflection at each sensor,
- deflection error tolerance in percent, and
- maximum number of iterations.

Once the input file is stored, the backcalculation step of the program can be executed. The program predicts modulus values one load at a time, and requires that the key-board operator be present throughout the program run to finish its backcalculation technique. The program does not automatically create an output file and therefore the final results must be printed, using the print screen key on the computer before continuing with the next deflection basin. This program takes approximately 0.5 minutes on a 386, 40 megahertz IBM PC or compatible computer.

PROCEDURE FOR STATISTICAL ANALYSIS

In this project all statistical work was performed by the Statistical Analysis System (SAS) computer package which can perform regression procedures, analysis of variance, and many other statistical operations. The analysis of variance (ANOVA) procedure was utilized during this project to develop information with which means can be tested to determine if one set of observations are significantly different from another. ANOVA calculations are recorded in an ANOVA table similar to that shown below.

Source	DF	SS	MS	F-value
Model	Df_m	SSM	MSM	F
Error	Df_e	SSE	MSE	
Corrected Total	Df_{ct}	SST		

The output table has the following column titles: source, degrees of freedom (df), sum of squares (SS), mean squares (MS), and F-value. The source column includes model, error, and corrected total categories. The degrees of freedom section includes the degrees of freedom for each of the three categories listed in the source column. The sum of squares column includes the sum of squares results for each of the three source categories. The mean squares column includes the mean squares of the model and error, the values for these two are calculated by dividing the SS by the df for the respective categories. The F-value is calculated by dividing the mean square of model (MSM) by the mean square of error (MSE) and this calculated value is compared with a tabulated F-values for the number of degrees of freedom as the model and the error terms to determine whether the source elements are significant or not.

In an attempt to determine which of the backcalculation programs produced average moduli most like the laboratory determined values, three significance tests were utilized; 1) Student-Newman-Keuls (SNK) Test for Variance, 2) Duncan's Multiple Range Test, and 3) Least Significant Difference (LSD) Test. All three tests use results from the ANOVA procedure.

Student-Newman-Keuls test is a good test because it allows investigation of all possible pairs of means in a sequential manner, has very good power, and keeps the level of significance constant for investigation of all pairs of means. The SNK test procedure is as follows. First arrange the means in rank position from largest to smallest.

RANK NUMBER	1	2	3	4
GROUP NAME	B	D	C	A
GROUP MEAN	8.7	6.8	5.7	5.0

Then prepare a table of differences between means from the largest differences (column K) to the smallest (column K-2) in all possible pairs forming a triangular arrangement. The differences for the first row are computed by subtracting from the largest mean (1) each of the other smaller means: 1-4, 1-3, 1-2 which correspond to the means for groups B-A, B-C, and B-D. The second row is computed by subtracting from the next largest mean (2) each of the other smaller means: 2-4, 2-3 which correspond to the means for groups D-A and D-C beginning with the largest difference for the K^{th} column. The third row is computed by subtracting from the next largest mean (3) each of the smaller means: 3-4 which correspond to the means for group C-A.

	k	k-1	k-2
	4	3	2
1	B-A	B-C	B-D
2	D-A	D-C	
3	C-A		

Next a list of the least significant ranges is calculated for each of the columns K, K-1, and K-2 using the following procedure:

$$R_k = q_\alpha(k,df)S_y \qquad \text{(Eq. 2a)}$$

$$R_{k-1} = q_\alpha(k-1,df)S_y \qquad \text{(Eq. 2b)}$$

$$R_{k-2} = q_\alpha(k-2,df)S_y \qquad \text{(Eq. 2c)}$$

where:

$q_\alpha(k,df)$ = upper percentage point for Studentized range for desired α (found in statistics tables).

α = Level of significance.

k = Number of means evaluated.

df = Degrees of freedom from error from the ANOVA table.

S_y = Standard error of the mean $(MSE/n)^{1/2}$.

MSE = Mean square of error from the ANOVA table.

The next step is to compare the values in the triangular table to the calculated value for R_k. Look at each diagonal element and compare R_k to the values in the column for k. If any value in the diagonal element is larger than the calculated value, R_k, then the two means are significantly different. Repeat the comparison for R_{k-1} and the differences in the diagonal element k-1 and for R_{k-2} and diagonal element k-2 (22).

Duncan's Multiple Range Test is a test that determines if a group's mean is significantly different from each other. The test is performed by taking all of the sample means (k), arranging them in increasing order of magnitude, and then calculating the differences between the adjacent sample means. Next, the existence of significant variation between each of the two groups of (k-1) adjacent ordered means is checked. The range of group one is computed by subtracting the first mean (the smallest) from the (k-1) mean, this value is compared to a standardized R_g value (defined later). If the standardized value is less than the calculated range then the first mean and the (k-1) mean are significantly different. The same procedure is repeated for the range of group 2, the second mean in order of magnitude is subtracted from the k^{th} mean (the largest). If a set does not give a significant result, it is concluded that the variability of means within that group of (k-1) is random and no further testing for differences within that group of (k-1) means is warranted. This result is indicated in the table of means by underlining with a common line the range of means that produced the not significant result. If there is a significant difference between the means, all the sets of (k-2) adjacent ordered means in the block are examined, and so on. This procedure is illustrated in the following section (23).

Group Means	A	B	C	D	E
(k = 5)					

where A is the smallest and E is the largest.

In the (k-1) step the interval for testing is 5-1=4, therefore mean A is compared to mean D and mean B is compared to mean E as these 2 sets are the only sets with a difference of 4. (D - A) and (E - B) are calculated and compared to the calculated R_g value. If (D - A) is larger than R_g then all means from A through D are significantly different and it is time to repeat the process but using (k-2) and an updated value for R_g. If (D-A) is smaller than R_g then there is no significant difference between the means from A through D, and no other tests are required for means A through D.

At each stage, the test consists of comparing the range of the group of adjacent means under study with a critical limit, R_g, which is calculated as:

$$R_g = C(g,\nu,\alpha)(MSE / n)^{1/2} \qquad \text{(Eq. 3)}$$

where

$C(g,\nu,\alpha)$ = a constant found in statistical tables,

g = number of groups,

ν = degrees of freedom for error, from ANOVA table,

α = significance level,

MSE = mean square of error, from ANOVA table,

n = number of observations in group.

Least Significant Difference (LSD) is a measure of how far apart the group means need to be to show significance. Significance can be determined if the difference between group means is greater than the LSD value.

$$LSD = (t_{\alpha, DFE})(S)(2/n)^{1/2} \quad \text{(Eq. 4)}$$

where α = significance level,

DFE = degrees of freedom for error, from ANOVA table,

$(t_{\alpha, DFE})$ = t-table value,

S = root mean square of error = $(MSE)^{1/2}$, from ANOVA table,

n = number of data per group.

These tests were selected because they represent the most commonly used tests in statistical research. Three tests were used because multiple comparisons using any one of the three tests, such as used in this project, are not faultless indicators; therefore three were used to see if any of the three would indicate significant differences from the different types of tests. However, it is important to note that when multiple comparisons are interpreted, failure to reject the hypothesis that two or more means are equal should not lead to the conclusion that the population means are in fact equal. Failure to reject the null hypothesis implies only that the difference between population means, if any, is not large enough to be detected with the given sample size (24).

STATISTICAL COMPARISONS OF MODULI

The deflection data collected by LTRC staff from the KUAB Falling Weight Deflectometer for each section is included in Volume 2 -- Appendix 3. Each section was tested at five different locations within the 500 feet length and at each test location four different loads were applied. The loads ranged from approximately 3,500 up to 14,000 pounds which correspond to axle loads of 7,000 to 28,000 pounds. Measured deflections from each load were input into each of the programs in order to backcalculate the layer modulus values for each pavement layer.

Initially, all of the load and deflection data were included in a single analysis and interpretation was found to be very difficult. All of the predicted moduli were significantly different from the laboratory data, primarily because of the stress sensitivity of some pavement layers. This can be expected since the laboratory moduli were developed for an 18 kip load stress level; therefore it was more appropriate to compare laboratory data with predicted data from the 9 kip wheel load.

Therefore, since the 18 kip single axle load is the design load for highway pavements, the project staff decided to concentrate on results with that load to determine if any of the backcalculation programs appeared to be superior to the others. This decision decreased the number of deflection basins to one per location, or five per section. Each program was run using both these individual deflection basins, which were evaluated for each section, and an average of the five deflection basins for each section with the average deflection basin used as input for each program. These average values are included in Volume 2 -- Appendix 4, and the computer generated moduli generated from both individual and average deflections are shown in Volume 2 -- Appendix 5.

When performing a statistical evaluation of the results from the programs, the sections were grouped by similar characteristics, i.e, the sections with black base layers were grouped together, the sections with a soil cement base were grouped together, and the sections with a cement stabilized sand clay gravel base were grouped together. Also sections with a soil cement base were analyzed separate from the control sections since the control sections had an unusually thick HMA bases (after combining the old surface and old base into one layer). Since Hadley's laboratory data showed the stabilized sand clay gravel and the soil cement material had virtually the same modulus value, these two base types were combined into one group, and analyzed both with and without the control sections. All of the above mentioned groupings were also evaluated using average moduli estimated from both individual and averaged deflections.

A comparison between predicted moduli and measured laboratory moduli that showed no statistical difference is denoted in the output Tables 4-10 by "no significant difference." Comparisons that were significantly differnt are denoted in the output tables by a blank. The statistical analysis output data have been summarized for each computer program to show for each pavement layer which base type results are not significantly different from the laboratory values and which statistical test produced the not significantly different result. The summary from this series of SAS output are contained in Tables 4-10 (the actual SAS

Table 4.

Results of Significance Test Which Compared The Various Material Moduli Predicted From Program 1 With The Laboratory Measured Moduli for Pavements With Different Bases

BASE TYPE	LAYER 1	LAYER 2	LAYER 3	LAYER 4
BLACK BASE[1]	1,2,3[2]			
AVG.[3] BLACK BASE	1,2,3			
SOIL CEMENT[1]	1	1,2,3		
AVG. SOIL CEMENT	1,2,3	1,2,3		
SOIL CEMENT[1] NO CONTROL	1,2,3		1	
AVG.[3] SOIL CEMENT NO CONTROL	1,2,3		1,2,3	
CEMENT TREATED SAND CLAY GRAVEL[1]	1		1,2,3	
AVG.[2] CEMENT TREATED SAND CLAY GRAVEL	1,2,3		1,2,3	
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1]				
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL	1,2,3	1,2,3		
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1] NO CONTROL	1			
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL NO CONTROL	1,2,3		1,2,3	

1. Moduli backcalculated from individual deflection basins.

2. Number Key
   1 = No significant difference from Student-Newman-Keuls test.
   2 = No significant difference from Duncan Multiple Range test.
   3 = No significant difference from Least Significant Difference test.

3. Moduli backcalculated from the average of five deflection basins.

Table 5.

Results of Significance Test Which Compared The Various Material Moduli Predicted From Program 2 With The Laboratory Measured Moduli for Pavements With Different Bases

BASE TYPE	LAYER 1	LAYER 2	LAYER 3	LAYER 4
BLACK BASE[1]	1,2,3[2]	1,2,3		
AVG.[3] BLACK BASE	1,2,3			1
SOIL CEMENT[1]	1,2,3	1,2,3		
AVG. SOIL CEMENT	1,2,3	1,2,3	1,2,3	
SOIL CEMENT[1] NO CONTROL	1,2,3		1,2,3	
AVG.[3] SOIL CEMENT NO CONTROL	1,2,3		1,2,3	1,2,3
CEMENT TREATED SAND CLAY GRAVEL[1]	1,2,3		1,2,3	
AVG.[2] CEMENT TREATED SAND CLAY GRAVEL	1,2,3		1,2,3	1,2,3
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1]	1,2,3	1,2		
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL	1,2,3	1,2,3	1,2,3	
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1] NO CONTROL	1,2,3		1,2	
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL NO CONTROL	1,2,3		1,2,3	1

1. Moduli backcalculated from individual deflection basins.

2. Number Key
   1 = No significant difference from Student-Newman-Keuls test.
   2 = No significant difference from Duncan Multiple Range test.
   3 = No significant difference from Least Significant Difference test.

3. Moduli backcalculated from the average of five deflection basins.

Table 6.

Results of Significance Test Which Compared The Various Material Moduli Predicted From Program 3 With The Laboratory Measured Moduli for Pavements With Different Bases

BASE TYPE	LAYER 1	LAYER 2	LAYER 3	LAYER 4
BLACK BASE[1]	1,2,3[2]			
AVG.[3] BLACK BASE	1,2,3			
SOIL CEMENT[1]				
AVG. SOIL CEMENT	1	1,2,3	1,2,3	
SOIL CEMENT[1] NO CONTROL	1		1,2,3	
AVG.[3] SOIL CEMENT NO CONTROL	1,2,3		1,2,3	
CEMENT TREATED SAND CLAY GRAVEL[1]	1		1,2,3	
AVG.[2] CEMENT TREATED SAND CLAY GRAVEL	1,2		1,2,3	
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1]				
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL	1,2,3	1,2,3	1,2,3	
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1] NO CONTROL	1,2,3		1,2,3	
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL NO CONTROL	1,2,3		1,2,3	

1. Moduli backcalculated from individual deflection basins.
2. Number Key
   1 = No significant difference from Student-Newman-Keuls test.
   2 = No significant difference from Duncan Multiple Range test.
   3 = No significant difference from Least Significant Difference test.
3. Moduli backcalculated from the average of five deflection basins.

Table 7.

Results of Significance Test Which Compared The Various Material Moduli Predicted From Program 4 With The Laboratory Measured Moduli for Pavements With Different Bases

BASE TYPE	LAYER 1	LAYER 2	LAYER 3	LAYER 4
BLACK BASE[1]	1,2,3[2]			
AVG.[3] BLACK BASE	1,2,3	1,2,3		
SOIL CEMENT[1]	1,2,3			
AVG. SOIL CEMENT	1,2,3	1,2,3	1,2,3	
SOIL CEMENT[1] NO CONTROL	1,2,3		1	
AVG.[3] SOIL CEMENT NO CONTROL	1,2,3		1,2,3	
CEMENT TREATED SAND CLAY GRAVEL[1]	1,2,3		1,2,3	
AVG.[2] CEMENT TREATED SAND CLAY GRAVEL	1		1,2,3	
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1]	1,2,3	1,2,3		
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL	1,2,3	1,2,3	1,2	
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1] NO CONTROL	1,2,3			
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL NO CONTROL	1,2,3		1,2,3	

1. Moduli backcalculated from individual deflection basins.

2. Number Key
   1 = No significant difference from Student-Newman-Keuls test.
   2 = No significant difference from Duncan Multiple Range test.
   3 = No significant difference from Least Significant Difference test.

3. Moduli backcalculated from the average of five deflection basins.

Table 8.

Results of Significance Test Which Compared The Various Material Moduli Predicted From Program 5 With The Laboratory Measured Moduli for Pavements With Different Bases

BASE TYPE	LAYER 1	LAYER 2	LAYER 3	LAYER 4
BLACK BASE[1]	1,2,3[2]			
AVG.[3] BLACK BASE	1,2,3	1		
SOIL CEMENT[1]	1,2,3	1,2,3		
AVG. SOIL CEMENT	1,2,3	1,2,3	1,2,3	
SOIL CEMENT[1] NO CONTROL	1,2,3		1	
AVG.[3] SOIL CEMENT NO CONTROL	1,2,3		1,2,3	
CEMENT TREATED SAND CLAY GRAVEL[1]	1,2,3		1,2,3	
AVG.[2] CEMENT TREATED SAND CLAY GRAVEL	1		1,2,3	
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1]	1,2,3	1,2,3		
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL	1,2,3	1,2,3	1,2,3	
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1] NO CONTROL	1,2,3		1	
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL NO CONTROL	1,2,3		1,2,3	

1. Moduli backcalculated from individual deflection basins.

2. Number Key
   1 = No significant difference from Student-Newman-Keuls test.
   2 = No significant difference from Duncan Multiple Range test.
   3 = No significant difference from Least Significant Difference test.

3. Moduli backcalculated from the average of five deflection basins.

Table 9.

Results of Significance Test Which Compared The Various Material Moduli Predicted From Program 6 With The Laboratory Measured Moduli for Pavements With Different Bases

BASE TYPE	LAYER 1	LAYER 2	LAYER 3	LAYER 4
BLACK BASE[1]				
AVG.[3] BLACK BASE	1,2,3[2]			1,2,3
SOIL CEMENT[1]	1,2,3	1,2,3		
AVG. SOIL CEMENT	1,2,3	1,2,3	1,2,3	1,2,3
SOIL CEMENT[1] NO CONTROL	1		1	1,2,3
AVG.[3] SOIL CEMENT NO CONTROL	1,2,3		1,2,3	1,2,3
CEMENT TREATED SAND CLAY GRAVEL[1]	1,2,3		1,2,3	1,2,3
AVG.[2] CEMENT TREATED SAND CLAY GRAVEL	1,2,3		1,2,3	1,2,3
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1]	1,2,3	1,2,3		
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL	1,2,3	1,2,3	1,2,3	1,2,3
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1] NO CONTROL	1		1	1,2,3
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL NO CONTROL	1,2,3		1,2,3	1,2,3

1. Moduli backcalculated from individual deflection basins.
2. Number Key
   1 = No significant difference from Student-Newman-Keuls test.
   2 = No significant difference from Duncan Multiple Range test.
   3 = No significant difference from Least Significant Difference test.
3. Moduli backcalculated from the average of five deflection basins.

Table 10.

Results of Significance Test Which Compared The Various Material Moduli Predicted From Program 7 With The Laboratory Measured Moduli for Pavements With Different Bases

BASE TYPE	LAYER 1	LAYER 2	LAYER 3	LAYER 4
BLACK BASE[1]	1,2[2]			
AVG.[3] BLACK BASE	1,2,3			
SOIL CEMENT[1]	1,2,3			
AVG. SOIL CEMENT	1,2,3	1,2,3	1,2	
SOIL CEMENT[1] NO CONTROL	1		1,2,3	
AVG.[3] SOIL CEMENT NO CONTROL	1,2,3		1,2,3	
CEMENT TREATED SAND CLAY GRAVEL[1]	1,2,3		1,2,3	
AVG.[3] CEMENT TREATED SAND CLAY GRAVEL			1,2,3	
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1]	1,2,3			
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL	1,2,3	1,2,3	1,2	
SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL[1] NO CONTROL	1		1,2,3	
AVG.[3] SOIL CEMENT AND CEMENT TREATED SAND CLAY GRAVEL NO CONTROL	1,2,3		1,2	

1. Moduli backcalculated from individual deflection basins.

2. Number Key
   1 = No significant difference from Student-Newman-Keuls test.
   2 = No significant difference from Duncan Multiple Range test.
   3 = No significant difference from Least Significant Difference test.

3. Moduli backcalculated from the average of five deflection basins.

output is included in Volume 2 -- Appendix 6). In order to more easily digest these results a summary table has been prepared to show the number of results which were not significantly different results by layer and by program. This analysis is described in the next section.

When attempting to evaluate all the programs to determine which one appears to work best for Louisiana materials, three things were considered; 1) results from the statistical analysis which determined for each program the number of times that calculated moduli results for each layer were not significantly different from the laboratory moduli determined by Hadley (15); 2) the percentage of times that the predicted modulus values go to either the upper or lower limit of the moduli range during the iterations in the backcalculation process; and 3) the capabilities and ease of use of each program.

Results of the Statistical Analysis of Modulus Results

In the statistical analysis, the backcalculated modulus for each layer was compared to the laboratory value determined for that material by Hadley (15). If the difference between the backcalculated and measured moduli was not significant, the program which generated the modulus from deflection data was judged to be an adequate prediction of modulus. Using the deflection data on all test sections, the results from the statistical analysis are summarized in Table 11 which was prepared from the data contained in Tables 4-10 showing by sections which layers had

Table 11.

Number of Section Types By Layer Where the Moduli Predicted From FWD Deflections Were Not Significantly Different From Measured Laboratory Moduli

Program	Layer 1	Layer 2	Layer 3	Layer 4
1	11	3	5	0
2	12	5	8	4
3	11	2	8	0
4	12	4	7	0
5	12	5	8	0
6	11	4	8	9
7	11	2	8	0

predicted moduli not significantly different from laboratory moduli for each program. In all cases a 5 percent level of significance was used. Based on the moduli results from program 1 as shown in Table 11:

a) The predicted moduli for layer 1 were not significantly different from the measured laboratory moduli for 11 of the 12 test sections.

b) The predicted moduli for layer 2 were not significantly different from the measured laboratory moduli for only three of the 12 section types. For the remaining nine sections types, the predicted moduli were significantly different from the laboratory values.

c) The predicted moduli for layer 3 were not significantly different from the measured laboratory moduli for only five of the 12 sections types. For the remaining seven sections, the predicted moduli were significantly different from the laboratory values.

d) For the subgrade moduli from program 1, all predicted moduli for the 12 section types were significantly different from the laboratory values.

The remaining six programs can be analyzed in the same manner as program 1 by examining the data in Table 11.

From Table 11, four of the programs appear to more accurately predict moduli than the rest. The programs with the larger overall numbers recorded in Table 11 are 2, 4, 5, and 6, with 2 and 6 having the largest numbers of non-significant results. The next section contains a program to program comparison of the output from these four.

(2 vs 4) -- For layers 2 and 3 program 2 has one more section where the predicted moduli are not significantly different from the lab data than does program 4, and for the subgrade program 2 has four sections where the predicted moduli are not significantly different from the laboratory data while program 4 has none (Table 11). Output from program 4 is not significantly different from the lab data for the average of all the black bases for layer 2 (Table 7) while output from program 2 is significantly different (Table 5). However, output from program 2 for individual deflection basins is not significantly different from the lab data for both black base and soil cement for layer 2 (Table 5) while outputs from program 4 are significantly different (Table 7).

(2 vs 5) -- For layers 1, 2, and 3 program 2 has the same number of section types where the predicted moduli are not significantly different from the lab values as program 5, however, for layer 4 (subgrade) program 2 has four sections showing results that are not significantly different while program 5 has none (Table 11). Results from programs 2 and 5 flip flop when comparing black base results from individual deflections, and average deflections. Output from program 2 has layer 2 for the black base section being not significantly different (Table 5) while program 5 does show significance (Table 8). However, output from program 5 is not significantly different for layer 2 for the average black base sections (Table 8), while program 2 does show significance (Table 5).

(2 vs 6) -- For layers 1 and 2 program 2 has one more section where the predicted moduli are not significantly different from the lab moduli than does program 6 (Table 11). Both programs have eight of the 12 layer 3 section types being not significantly different from the measured laboratory moduli, while for layer 4 the predicted moduli for the subgrade is not significantly different for five more section types for program 6 than for program 2. For layer 2 black base materials, program 2 shows non-significant results (Table 5), while program 6 does not (Table 9). For the following section types, program 6 predicts subgrade modulus not significantly different from lab data (Table 9) while, program 2 shows them being significantly different (Table 5): average of soil cement, soil cement no control, sand clay gravel, average of soil cement and sand clay gravel, and soil cement and sand clay gravel no control.

(4 vs 5) -- For layer 1 both programs have the same number of not significantly different results. Program 5 has one more section being not significantly different than program 6 for both layers 2 and 3. For layer 4 neither program has any not significant values. Output from program 5 has a not significantly different value for layer 2 of the soil cement section (Table 8) while output from program 4 does not (Table 7). Program 5 also has a not significant result for layer 3 of the soil cement and sand clay gravel no control section (Table 8), while program 4 does not (Table 7).

(4 vs 6) -- For layer 1 program 4 has one more section being not significantly different than program 6. Both programs have four of the 12 layer 2 section types being not significantly different from the measured laboratory moduli, while for layer 4, program 6 has one more section being not significantly different than program 4 for layer 3, and nine more for layer 4. Output from program 4 has layer 1 of the black base section type showing not significantly different results (Table 7), while output from program 6 does not (Table 9). For layer 2 program 4 has the average black base section type being not significantly different (Table 7), while program 6 is significantly different (Table 9). Also for layer 2, program 6 has the soil cement section type being not significantly different (Table 9), while program 4 is significantly different (Table 7). Program 6 has the soil cement section type for layer 3 being not significantly different (Table 9), while program 4 is significantly different (Table 7).

(5 vs 6) -- For layers 1 and 2 program 5 has one more section type where the predicted moduli are not significant different from the lab data than does program 6, but the same number of not significantly different values for layer 3 (Table 11). Program 6 has nine section types being not significantly different for layer 4 (Table 9) while program 5 has none (Table 8). Program 5 has layer 2 of the black base section type and layer 3 of the average black base section type being not significant (Table 8), while program 6 does not (Table 21).

After noting the above comparisons, programs 2 and 6 (MODULUS Step 3 and WESDEF) appear to more adequately predict values comparable with laboratory results more often than the others.

Percentage at Limit

It is also important to determine the number of times that a computer program reaches the limit of the moduli range in an attempt to converge on a solution. When a program goes to a limit before converging, the predicted moduli may be suspect since the program tried to go beyond the limits of the moduli range. These limits are set at a reasonable range to give the program considerable flexibility in converging on a solution, however, when the predicted values are at a limit the results may be questioned. Output from the statistical analysis shows which programs predicted moduli that were not significantly different from the measured laboratory moduli. These two types of information have been summarized in Tables 12-23 by type of base material and pavement layer by indicating with 1) an asterisk (*) if the moduli predicted by the program are significantly different (not desirable) from the laboratory measured moduli, and 2) by a number, if the predicted moduli are not significantly different (desirable) from the laboratory measured moduli, which represents the percent of time that the predicted modulus is at either the upper or lower limit of the allowable range input by the user or as calculated internally by the program. Tables 24 and 25 contain a summary of Tables 12-23 for the percentages of predicted moduli values that are at either the upper or lower limit for each program.

Table 12.

Significance Test Results and Percent of Values at Either the Upper or Lower Modulus Limit for Black Base Section Results for Each Program From Individual Deflection Basins

Test	Program	Percent of Values at Limit			
		Layer 1	Layer 2	Layer 3	Layer 4
SNK	1	1.1[1]	*	*	*
SNK	2	14.4	26.7	*	*
SNK	3	40.0	*	*	*
SNK	4	22.2	*	*	*
SNK	5	28.9	*	*	*
SNK	6	*	*	*	*
SNK	7	51.1	*	*	*
DUNCAN	1	1.1	*	*	*
DUNCAN	2	14.4	26.7	*	*
DUNCAN	3	40.0	*	*	*
DUNCAN	4	22.2	*	*	*
DUNCAN	5	28.9	*	*	*
DUNCAN	6	*	*	*	*
DUNCAN	7	51.1	*	*	*
LSD	1	1.1	*	*	*
LSD	2	14.4	26.7	*	*
LSD	3	40.0	*	*	*
LSD	4	22.2	*	*	*
LSD	5	28.9	*	*	*
LSD	6	*	*	*	*
LSD	7	*	*	*	*

* Means there is a significant difference between program predicted and laboratory measured moduli.

[1] Numbers in the column is the percent of values at either an upper or lower modulus limit for results showing no significant difference between predicted and laboratory measured moduli.

Table 13.

Significance Test Results and Percent of Values at Either the Upper or Lower Modulus Limit for Black Base Section Results for Each Program From Averaged Deflection Basins

TEST	Program	Percent of Values at Limit			
		Layer 1	Layer 2	Layer 3	Layer 4
SNK	1	1.1[1]	*	*	*
SNK	2	14.4	*	*	0
SNK	3	40.0	*	*	*
SNK	4	22.2	38.9	*	*
SNK	5	28.9	27.8	*	*
SNK	6	28.9	*	*	0
SNK	7	51.1	*	*	*
DUNCAN	1	1.1	*	*	*
DUNCAN	2	14.4	*	*	*
DUNCAN	3	40.0	*	*	*
DUNCAN	4	22.2	38.9	*	*
DUNCAN	5	28.9	*	*	*
DUNCAN	6	28.9	*	*	0
DUNCAN	7	51.1	*	*	*
LSD	1	1.1	*	*	*
LSD	2	14.4	*	*	*
LSD	3	40.0	*	*	*
LSD	4	22.2	38.9	*	*
LSD	5	28.9	*	*	*
LSD	6	28.9	*	*	0
LSD	7	51.1	*	*	*

* Means there is a significant difference between program predicted and laboratory measured moduli.

[1] Numbers in the column is the percent of values at either an upper or lower modulus limit for results showing no significant difference between predicted and laboratory measured moduli.

Table 14.

Significance Test Results and Percent of Values at Either the Upper or Lower Modulus Limit for Soil Cement Section Results for Each Program From Individual Deflection Basins

Test	Program	Percent of Values at Limit			
		Layer 1	Layer 2	Layer 3	Layer 4
SNK	1	1.1[1]	8.8	*	*
SNK	2	14.4	26.7	*	*
SNK	3	*	*	*	*
SNK	4	22.2	*	*	*
SNK	5	28.9	27.8	*	*
SNK	6	28.9	42.2	*	*
SNK	7	51.1	*	*	*
DUNCAN	1	*	8.8	*	*
DUNCAN	2	14.4	26.7	*	*
DUNCAN	3	*	*	*	*
DUNCAN	4	22.2	*	*	*
DUNCAN	5	28.9	27.8	*	*
DUNCAN	6	28.9	42.2	*	*
DUNCAN	7	51.1	*	*	*
LSD	1	*	8.8	*	*
LSD	2	14.4	26.7	*	*
LSD	3	*	*	*	*
LSD	4	22.2	*	*	*
LSD	5	28.9	27.8	*	*
LSD	6	28.9	42.2	*	*
LSD	7	51.1	*	*	*

* Means there is a significant difference between program predicted and laboratory measured moduli.

[1] Numbers in the column is the percent of values at either an upper or lower modulus limit for results showing no significant difference between predicted and laboratory measured moduli.

Table 15.

Significance Test Results and Percent of Values at Either the Upper or Lower Modulus Limit for Soil Cement Section Results for Each Program From Averaged Deflection Basins

Test	Program	Percent of Values at Limit			
		Layer 1	Layer 2	Layer 3	Layer 4
SNK	1	1.1[1]	8.8	*	*
SNK	2	14.4	26.7	38.9	*
SNK	3	40.0	34.4	48.9	*
SNK	4	22.2	38.9	62.2	*
SNK	5	28.9	27.8	48.9	*
SNK	6	28.9	42.2	55.6	0
SNK	7	51.1	42.2	54.4	*
DUNCAN	1	1.1	8.8	*	*
DUNCAN	2	14.4	26.7	38.9	*
DUNCAN	3	*	34.4	48.9	*
DUNCAN	4	22.2	38.9	62.2	*
DUNCAN	5	28.9	27.8	48.9	*
DUNCAN	6	28.9	42.2	55.6	0
DUNCAN	7	51.1	42.2	54.4	*
LSD	1	1.1	8.8	*	*
LSD	2	14.4	26.7	38.9	*
LSD	3	*	34.4	48.9	*
LSD	4	22.2	38.9	62.2	*
LSD	5	28.9	27.8	48.9	*
LSD	6	28.9	42.2	55.6	0
LSD	7	51.1	42.2	*	*

* Means there is a significant difference between program predicted and laboratory measured moduli.

[1] Numbers in the column is the percent of values at either an upper or lower modulus limit for results showing no significant difference between predicted and laboratory measured moduli.

Table 16.

Significance Test Results and Percent of Values at Either the Upper or Lower Modulus Limit for Soil Cement (No Control) Section Results for Each Program From Individual Deflection Basins

Test	Program	Percent of Values at Limit			
		Layer 1	Layer 2	Layer 3	Layer 4
SNK	1	1.1[1]	*	22.2	*
SNK	2	11.1	*	27.8	*
SNK	3	25.6	*	26.7	*
SNK	4	17.8	*	42.2	*
SNK	5	16.7	*	27.8	*
SNK	6	26.7	*	36.7	0
SNK	7	41.1	*	34.4	*
DUNCAN	1	0.0	*	*	*
DUNCAN	2	11.1	*	27.8	*
DUNCAN	3	*	*	26.7	*
DUNCAN	4	17.8	*	*	*
DUNCAN	5	16.7	*	*	*
DUNCAN	6	*	*	*	0
DUNCAN	7	*	*	34.4	*
LSD	1	0	*	*	*
LSD	2	11.1	*	27.8	*
LSD	3	*	*	26.7	*
LSD	4	17.8	*	*	*
LSD	5	16.7	*	*	*
LSD	6	*	*	*	0
LSD	7	*	*	34.4	*

* Means there is a significant difference between program predicted and laboratory measured moduli.

[1] Numbers in the column is the percent of values at either an upper or lower modulus limit for results showing no significant difference between predicted and laboratory measured moduli.

Table 17.

Significance Test Results and Percent of Values at Either the Upper or Lower Modulus Limit for Soil Cement (No Control) Section Results for Each Program From Averaged Deflection Basins

Test	Program	Percent of Values at Limit			
		Layer 1	Layer 2	Layer 3	Layer 4
SNK	1	0[1]	*	22.2	*
SNK	2	11.1	*	27.8	0
SNK	3	25.6	*	26.7	*
SNK	4	17.8	*	42.2	*
SNK	5	16.7	*	27.8	*
SNK	6	26.7	*	36.7	0
SNK	7	41.1	*	34.4	*
DUNCAN	1	0	*	22.2	*
DUNCAN	2	11.1	*	27.8	0
DUNCAN	3	25.6	*	26.7	*
DUNCAN	4	17.8	*	42.2	*
DUNCAN	5	16.7	*	27.8	*
DUNCAN	6	26.7	*	36.7	0
DUNCAN	7	41.1	*	34.4	*
LSD	1	0	*	22.2	*
LSD	2	11.1	*	27.8	0
LSD	3	25.6	*	26.7	*
LSD	4	17.8	*	42.2	*
LSD	5	16.7	*	27.8	*
LSD	6	26.7	*	26.7	0
LSD	7	41.1	*	34.4	*

* Means there is a significant difference between program predicted and laboratory measured moduli.

[1] Numbers in the column is the percent of values at either an upper or lower modulus limit for results showing no significant difference between predicted and laboratory measured moduli.

Table 18.

Significance Test Results and Percent of Values at Either the Upper or Lower Modulus Limit for Cement Treated Sand Clay Gravel Section Results for Each Program From Individual Deflection Basins

Test	Program	Percent of Values at Limit			
		Layer 1	Layer 2	Layer 3	Layer 4
SNK	1	1.1[1]	*	40.9	*
SNK	2	14.4	*	38.9	*
SNK	3	40.0	*	48.9	*
SNK	4	22.2	*	62.2	*
SNK	5	28.9	*	48.9	*
SNK	6	28.9	*	55.6	0
SNK	7	51.1	*	54.4	*
DUNCAN	1	*	*	40.9	*
DUNCAN	2	14.4	*	38.9	*
DUNCAN	3	*	*	48.9	*
DUNCAN	4	22.2	*	62.2	*
DUNCAN	5	28.9	*	48.9	*
DUNCAN	6	28.9	*	55.6	0
DUNCAN	7	51.1	*	54.4	*
LSD	1	*	*	40.9	*
LSD	2	14.4	*	38.9	*
LSD	3	*	*	48.9	*
LSD	4	22.2	*	62.2	*
LSD	5	28.9	*	48.9	*
LSD	6	28.9	*	55.6	0
LSD	7	51.1	*	54.4	*

* Means there is a significant difference between program predicted and laboratory measured moduli.

[1] Numbers in the column is the percent of values at either an upper or lower modulus limit for results showing no significant difference between predicted and laboratory measured moduli.

Table 19.

Significance Test Results and Percent of Values at Either the Upper or Lower Modulus Limit for Cement Treated Sand Clay Gravel Section Results for Each Program From Averaged Deflection Basins

Test	Program	Percent of Values at Limit			
		Layer 1	Layer 2	Layer 3	Layer 4
SNK	1	1.1[1]	*	40.9	*
SNK	2	14.4	*	38.9	0
SNK	3	40.0	*	48.9	*
SNK	4	22.2	*	62.2	*
SNK	5	28.9	*	48.9	*
SNK	6	28.9	*	55.6	0
SNK	7	*	*	54.4	*
DUNCAN	1	1.1	*	40.9	*
DUNCAN	2	14.4	*	38.9	0
DUNCAN	3	40.0	*	48.9	*
DUNCAN	4	*	*	62.2	*
DUNCAN	5	*	*	48.9	*
DUNCAN	6	28.9	*	55.6	0
DUNCAN	7	*	*	54.4	*
LSD	1	1.1	*	40.9	*
LSD	2	14.4	*	38.9	0
LSD	3	*	*	48.9	*
LSD	4	*	*	62.2	*
LSD	5	*	*	48.9	*
LSD	6	28.9	*	55.6	0
LSD	7	*	*	54.4	*

* Means there is a significant difference between program predicted and laboratory measured moduli.

[1] Numbers in the column is the percent of values at either an upper or lower modulus limit for results showing no significant difference between predicted and laboratory measured moduli.

Table 20.

Significance Test Results and Percent of Values at Either the Upper or Lower Modulus Limit for Soil Cement and Cement Treated Sand Clay Gravel Section Results for Each Program From Individual Deflection Basins

Test	Program	Percent of Values at Limit			
		Layer 1	Layer 2	Layer 3	Layer 4
SNK	1	*[1]	*	*	*
SNK	2	14.4	26.7	*	*
SNK	3	*	*	*	*
SNK	4	22.2	38.9	*	*
SNK	5	28.9	27.8	*	*
SNK	6	28.9	42.2	*	*
SNK	7	51.1	*	*	*
DUNCAN	1	*	*	*	*
DUNCAN	2	14.4	26.7	*	*
DUNCAN	3	*	*	*	*
DUNCAN	4	22.2	38.9	*	*
DUNCAN	5	28.9	27.8	*	*
DUNCAN	6	28.9	42.2	*	*
DUNCAN	7	51.1	*	*	*
LSD	1	*	*	*	*
LSD	2	14.4	*	*	*
LSD	3	*	*	*	*
LSD	4	22.2	38.9	*	*
LSD	5	28.9	27.8	*	*
LSD	6	28.9	42.2	*	*
LSD	7	51.1	*	*	*

* Means there is a significant difference between program predicted and laboratory measured moduli.

[1] Numbers in the column is the percent of values at either an upper or lower modulus limit for results showing no significant difference between predicted and laboratory measured moduli.

Table 21.

Significance Test Results and Percent of Values at Either the Upper or Lower Modulus Limit for Soil Cement and Cement Treated Sand Clay Gravel Section Results for Each Program From Averaged Deflection Basins

Test	Program	Percent of Values at Limit			
		Layer 1	Layer 2	Layer 3	Layer 4
SNK	1	1.1[1]	8.8	*	*
SNK	2	14.4	26.7	38.9	*
SNK	3	40.0	34.4	48.9	*
SNK	4	22.2	38.9	62.2	*
SNK	5	28.9	27.8	48.9	*
SNK	6	28.9	42.2	55.6	0
SNK	7	51.1	42.2	54.4	*
DUNCAN	1	1.1	8.8	*	*
DUNCAN	2	14.4	26.7	38.9	*
DUNCAN	3	40.0	34.4	48.9	*
DUNCAN	4	22.2	38.9	62.2	*
DUNCAN	5	28.9	27.8	48.9	*
DUNCAN	6	28.9	42.2	55.6	0
DUNCAN	7	51.1	42.2	54.4	*
LSD	1	1.1	8.8	*	*
LSD	2	14.4	26.7	38.9	*
LSD	3	40.0	34.4	48.9	*
LSD	4	22.2	38.9	*	*
LSD	5	28.9	27.8	48.9	*
LSD	6	28.9	42.2	55.6	0
LSD	7	51.1	42.2	*	*

* Means there is a significant difference between program predicted and laboratory measured moduli.

[1] Numbers in the column is the percent of values at either an upper or lower modulus limit for results showing no significant difference between predicted and laboratory measured moduli.

Table 22.

Significance Test Results and Percent of Values at Either the Upper or Lower Modulus Limit for Soil Cement and Cement Treated Sand Clay Gravel (No Control) Section Results for Each Program From Individual Deflection Basins

Test	Program	Percent of Values at Limit			
		Layer 1	Layer 2	Layer 3	Layer 4
SNK	1	0[1]	*	*	*
SNK	2	11.1	*	27.8	*
SNK	3	25.6	*	26.7	*
SNK	4	17.8	*	*	*
SNK	5	16.7	*	27.8	*
SNK	6	26.7	*	36.7	0
SNK	7	41.1	*	34.4	*
DUNCAN	1	*	*	*	*
DUNCAN	2	11.1	*	27.8	*
DUNCAN	3	25.6	*	26.7	*
DUNCAN	4	17.8	*	*	*
DUNCAN	5	16.7	*	*	*
DUNCAN	6	*	*	*	0
DUNCAN	7	*	*	34.4	*
LSD	1	*	*	*	*
LSD	2	11.1	*	*	*
LSD	3	25.6	*	26.7	*
LSD	4	17.8	*	*	*
LSD	5	16.7	*	*	*
LSD	6	*	*	*	0
LSD	7	*	*	34.4	*

* Means there is a significant difference between program predicted and laboratory measured moduli.

[1] Numbers in the column is the percent of values at either an upper or lower modulus limit for results showing no significant difference between predicted and laboratory measured moduli.

Table 23.

Significance Test Results and Percent of Values at Either the Upper or Lower Modulus Limit for Soil Cement and Cement Treated Sand Clay Gravel (No Control) Section Results for Each Program From Averaged Deflection Basins

Test	Program	Percent of Values at Limit			
		Layer 1	Layer 2	Layer 3	Layer 4
SNK	1	0[1]	*	22.2	*
SNK	2	11.1	*	27.8	0
SNK	3	25.6	*	26.7	*
SNK	4	17.8	*	42.2	*
SNK	5	16.7	*	27.8	*
SNK	6	26.7	*	36.7	0
SNK	7	41.1	*	34.4	*
DUNCAN	1	0	*	22.2	*
DUNCAN	2	11.1	*	27.8	*
DUNCAN	3	25.6	*	26.7	*
DUNCAN	4	17.8	*	42.2	*
DUNCAN	5	16.7	*	27.8	*
DUNCAN	6	26.7	*	36.7	0
DUNCAN	7	41.1	*	34.4	*
LSD	1	0	*	22.2	*
LSD	2	11.1	*	27.8	*
LSD	3	25.6	*	26.7	*
LSD	4	17.8	*	42.2	*
LSD	5	16.7	*	27.8	*
LSD	6	26.7	*	26.7	0
LSD	7	41.1	*	*	*

* Means there is a significant difference between program predicted and laboratory measured moduli.

[1] Numbers in the column is the percent of values at either an upper or lower modulus limit for results showing no significant difference between predicted and laboratory measured moduli.

Table 24.

Frequency and Percentage of Times the Predicted Moduli Was At a Limit, When Control Sections Were Included

Program	Layer 1		Layer 2		Layer 3		Layer 4	
	# at limit	% at limit	# at limit	% at limit	# at limit	% at limit	# at limit	% at limit
1	1	1.1	8	8.8	36	40.0	0	0.0
2	13	14.4	24	26.7	35	38.9	0	0.0
3	36	40.0	31	34.4	49	48.9	1	1.1
4	20	22.2	35	38.9	56	62.2	0	0.0
5	26	28.9	25	27.8	44	48.9	0	0.0
6	26	28.9	38	42.2	50	55.5	0	0.0
7	46	51.1	38	42.2	49	54.4	12	13.2

Table 25.

Frequency and Percentage of Times Predicted Moduli Was At a Limit, When Control Sections Were Not Included

Program	Layer 1		Layer 2		Layer 3		Layer 4	
	# at limit	% at limit	# at limit	% at limit	# at limit	% at limit	# at limit	% at limit
1	0	0.0	4	4.4	16	22.2	0	0.0
2	10	11.1	18	20.0	25	27.8	0	0.0
3	23	25.6	27	30.0	24	26.7	0	0.0
4	16	17.8	20	22.2	38	42.2	0	0.0
5	15	16.7	17	18.9	25	27.8	0	0.0
6	24	26.7	30	33.3	33	36.7	0	0.0
7	37	41.1	33	36.7	31	34.4	4	4.4

Results from Tables 24 and 25 indicate that predicted moduli for programs 1 and 2 were at a limit less than the other programs. However, when looking at the previous step where the programs were compared by number of not significantly different output values, it was observed that programs 2 and 6 gave the best results compared to the rest. When comparing the results from Table 24 for programs 2 and 6 it can be seen that program 2 goes to the limit 58 percent less for layer 1, 40 percent less for layer 2 and 24 percent less for layer 3 than for program 6. Table 25 shows a similar trend with both programs going to limits less when the control sections are eliminated from the analysis. Only program 1 consistently performed better than program 2 in going to the limit a smaller number of times. However, based on the results from Table 11, program 2 is superior to program 1 in backcalculating moduli that are not significantly different from the laboratory determined moduli.

Capabilities and Ease of Program Use

Now comparing the two best programs, 2 and 6, one very important difference between the two is that with MODULUS multiple deflection bowls can be run at the same time, while WESDEF can only evaluate one deflection bowl per run. Secondly, the MODULUS program comes with an extensive user's manual while the projects staff received no formal user's manual with WESDEF. Additionally, the authors are of the opinion that updates to MODULUS will be well documented and easily obtained since it has been adopted for use in the

Strategic Highway Research Program (SHRP) Long Term Pavement Performance (LTPP) program. Finally, the WESDEF output values were at either the upper or the lower limits of the moduli range more often than the output from MODULUS.

COMPARISONS OF RESULTS FROM AVERAGE DEFLECTIONS vs INDIVIDUAL DEFLECTIONS

When considering the procedure to be used in collecting field data for use in backcalculation of moduli to be used in pavement design, the engineer is faced with a decision as to whether to 1) take individual deflection basins and backcalculate moduli from each or, 2) make multiple drops at each location, average the deflections and use the average deflection basin to backcalculate moduli.

In an attempt to determine which of these procedures is superior, the project staff first backcalculated moduli from each deflection basin as shown in Volume 2 -- Appendix 5. Each of the five deflection basins taken on each section for the 18,000 pound axle load were then assumed to be replicate drops even though each was taken from a different location. The average deflection basin was generated by averaging the five readings at each sensor and then using that average basin as input for each program. Project investigators recognize that the variation among these five drops at five different locations should exceed the variation that would occur if the five drops had occurred at the same location.

Therefore calculating the average in this manner should be a worst case test to determine if the moduli from the average deflection basin was superior to the moduli from individual deflection basins. The data which forms the basin for this comparison are found in Tables 12-23.

The comparisons between the averaged deflection data and the individual deflection data can be made by studying the data in adjacent sets of tables: for example, to compare the moduli results from individual and average deflection basins for the black base type pavements the reader is directed to Tables 12 and 13; for soil cement base type pavements see Tables 18 and 19; and for the combination of soil cement and cement stabilized sand clay gravel see Tables 20 and 21. These tables contain the significant test results for all seven programs. However since programs 2 and 6 have been identified as the best candidates for potential use in Louisiana, results for each base type for programs 2 and 6 have been summarized in Table 26. The comparison data in Table 26 is arranged in each block of the table so that the results from individual deflection basins are shown to the left of the slash and the results from the average deflection basin are on the right of the slash. Results form each different base type is also separated in the table. A careful review of the data in Table 26 will show that for the soil cement, cement stabilized sand clay gravel and the combination of all cement stabilized bases the moduli predicted from the average basin was always superior to the moduli predicted form the individual basins for both programs 2 and 6. That is to say, there are fewer asterisks on the right side of the slash than on the left side of the slash. The only base type that did not show uniform improvement when using the average deflection basin to calculate moduli was the black base and specifically layer 2 using program 2. The authors have no reasonable explanation for this occurrence. Because of the improvements in the prediction of moduli for layers 3 and 4 that arise from using the average deflection basin, the authors recommend that backcalculated moduli be predicted from an average deflection basin rather than from individual deflection basins. Since the thrust of this investigation has been directed toward developing information for use in pavement design using the 1986 AASHTO Design Guide, the researchers suggest that deflection data be secured using only the 9,000 pound load which corresponds to an 18,000 pound single axle load and that the deflection from five replicate drops be averaged as input into program 2, MODULUS 4.0 step 3. Moduli predicted from this procedure can then be plotted along the highway section to determine where any subsections need to be divided up for individual designs.

SUMMARY

After analyzing the programs on the three different levels presented in this chapter, it appears that program 2 (MODULUS 4.0) is the best choice for use in Louisiana. It was observed in the significance comparison that programs 2 and 6 were about the same with program 2 being a little better for layers 1 and 2, while program 6 was a little better for layer 4. The next level of comparison, number of times a predicted value went to the limit, showed program 2 to be much better than program 6. Finally, in the third level of comparison, capabilities and ease of use; it can be seen that program 2 is superior to program 6 in both capabilities and ease of use.

CONCLUSIONS

As stated in the results, MODULUS 4.0 run utilizing step 3 the "Run a Full Analysis" option (step 2) appears to be the best choice for use in the state of Louisiana. It was observed to be one of two programs to give the best comparison between predicted and laboratory moduli values than the other five programs in the statistical analysis. Also it was judged to be the best program in the other two analysis, number of times the predicted value went to the limit, and the capabilities and ease of use.

For MODULUS 4.0, the statistical analysis showed the moduli values predicted from the average deflection data to be better estimates of laboratory moduli than those predicted from the individual deflection data for all base types except for layer 2 of some sections with a black base. The results indicate that moduli predicted from an average deflection basin calculated from five individual deflection basins from a 9,000 pound load produced better estimate of laboratory moduli than moduli predicted from individual deflection basins.

Future users of the MODULUS 4.0 program should be reminded, however, that results from program must be evaluated using sound engineering judgement. Because the modulus values approached the limits of reasonable values for 14.4 percent of the deflection bowls for layer 1, 26.8 percent for layer 2, and 38.9 percent for layer 3 and that layer 4 compared favorably to laboratory test data in only 33 percent of the section types, one must conclude that the method may not always produce reasonable results. Good engineering judgement must be applied to recognize these output which might be questionable. Such cases may require that the deflection data be looked at, that checks be made on cross-section elements, or that the deflection survey be repeated.

A limitation of this analysis of programs is that the backcalculated moduli are compared to laboratory moduli which were assumed to be the correct values. Current testing underway as part of the Strategic Highway Research Program indicates that there can be significant variability in M_R values measured in the laboratory. However, improvements in the testing procedure and equipment have been and continue to be realized in this area, so that confidence in future comparisons such as these will continue to grow as these improvements are made and as experience is gained.

RECOMMENDATIONS

The authors recommend that the program MODULUS 4.0 be used to predict moduli from the FWD data, and that the average of five deflection basins be used to estimate the moduli of the pavement layers. The users manual for MODULUS 4.0 is included in Volume 2 -- Appendix 7. However, future studies are necessary to further evaluate the validity of using MODULUS 4.0.

A. MODULUS 4.0 should be evaluated with a wider variety of pavement structures and subgrade types that are spread throughout the State of Louisiana to provide a broader assessment than was possible in this project.

B. The deflection data from the FWD should be taken repeatedly (at least five drops) for the same point at many different points per section. This will enable researchers to evaluate and determine the "optimum" number of drops and test locations needed to properly evaluate a pavement.

C. Only the design load (approximately 9,000 pounds for a wheel load on an 18 kip single axle load) needs to be applied unless the stress sensitivity of the pavement materials is of interest.

D. Laboratory tests, using the improvements continually being realized in M_R laboratory testing, should be conducted in conjunction with the field testing to provide a wider basis of comparison between backcalculated and laboratory measured M_R values. Since LTRC currently has a project underway to develop

Table 26.
Comparisons of Results from Programs 2 and 6 Showing the Effects of Using Individual and Average Deflections On Significance Test Results and Percent of Moduli Values at Either the Upper or Lower Limit for Both Test Sections and Control Sections

Test	Program	Base Type	Layer 1	Layer 2	Layer 3	Layer 4
			Percent of Values at Limit			
SNK	2	Black	14.4[1]/14.4[2]	26.7/*[3]	*/*	*/0
	6		*/28.9	*/*	*/*	*/0
Duncan	2		14.4/14.4	26.7/*	*/*	*/*
	6		*/28.9	*/*	*/*	*/0
LSD	2		14.4/14.4	26.7/*	*/*	*/0
	6		*/28.9	*/*	*/*	*/0
SNK	2	Soil Cement	14.4/14.4	26.7/26.7	*/38.9	*/0
	6		28.9/28.9	42.2/42.2	*/55.6	*/0
Duncan	2		14.4/14.4	26.7/26.7	*/38.9	*/*
	6		28.9/28.9	42.2/42.2	*/55.6	*/0
LSD	2		14.4/14.4	26.7/26.7	*/38.9	*/*
	6		28.9/28.9	42.2/42.2	*/55.6	*/0
SNK	2	Cement Stabilized Sand Clay Gravel	14.4/14.4	*/*	38.9/38.9	*/*
	6		28.9/28.9	*/*	55.6/55.6	0/0
Duncan	2		14.4/14.4	*/*	38.9/38.9	*/0
	6		28.9/28.9	*/*	55.6/55.6	0/0
LSD	2		14.4/14.4	*/*	38.9/38.9	*/0
	6		28.9/28.9	*/*	55.6/55.6	0/0
SNK	2	Soil Cement and Cement Stabilized Sand Clay Gravel	14.4/14.4	26.7/26.7	*/38.9	*/*
	6		28.9/28.9	42.2/42.2	*/55.6	*/0
Duncan	2		14.4/14.4	26.7/26.7	*/38.9	*/*
	6		28.9/28.9	42.2/42.2	*/55.6	*/0
LSD	2		14.4/14.4	26.7/26.7	*/38.9	*/*
	6		28.9/28.9	42.2/42.2	*/55.6	*/0

[1] First number is percent of moduli at upper or lower limit as calculated from individual deflection basins.
[2] Second number is percent of moduli at upper or lower limit as calculated from average deflection basins.
[3] * means there is a significant difference between program predicted and laboratory measured moduli.

laboratory procedures for measuring M_R, this recommendation is a logical extension of that work.

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